684

3087

A095556

A095 556

TARADCOM

R and D LABORATORY

TECHNICAL REPORT

NO. ~~12519~~ 12517

FORGING OF POWDER

METALLURGY GEARS

CONTRACT DAAK-30-78-C-0029

by B. L. Ferguson, TRW

D. T. Ostberg, TARADCOM

U.S. ARMY TANK-AUTOMOTIVE
RESEARCH AND DEVELOPMENT COMMAND
Warren, Michigan 48090

20020801115

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ~~12519~~ 12517	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) Forging of Powder Metallurgy Gears		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER ER-8037-F
7. AUTHOR(*s*) B. L. Ferguson D. T. Ostberg		8. CONTRACT OR GRANT NUMBER(*s*) DAAK-30-78-C-0029
9. PERFORMING ORGANIZATION NAME AND ADDRESS TRW Materials Technology Cleveland, Ohio		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Tank-Automotive Research & Development Command DRDTA-RCKM Warren, MI 48090		12. REPORT DATE May, 1980
		13. NUMBER OF PAGES 73
14. MONITORING AGENCY NAME & ADDRESS(*If different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for Public Release, Distribution Unlimited

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Forging
Powder Forging
Die Design
Composite Structures
Cold Isostatic Pressing (CIP)

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

The objective of this program was to produce a very near-net shape spur gear by isothermal forging of a powder metallurgy 4600 grade preform. Die fill and densification on test coupons were complete at a forging temperature of 1650F (900C), pressure of 10 tsi (140 MPa) with a dwell time of 15 min. Materials processed in this manner exhibited toughness and ductility, comparable to that in cast/wrought material.

Composite preforms consisting of a P/M gear and a wrought shaft were cold

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

~~12519~~ 12517

Final Technical Report

FORGING OF POWDER METALLURGY GEARS

Contract DAAK-30-78-C-0029

By

B. L. Ferguson

May 1980

Prepared For

U. S. Army Tank Automotive
Research and Development Command
Warren, Michigan

TRW Materials Technology
23555 Euclid Avenue
Cleveland, Ohio 44117

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

FOREWORD

This final report covers work performed from April 1978 to February 1980 on Contract DAAK30-78-C-0029. The contract was managed by the U.S. Army Tank-Automotive Research and Development Command (TARADCOM), Warren, Michigan with Kerold Chesney (retired), Vinod Patel (deceased), and Don Ostberg serving sequentially as the Program Technical Representative.

The program was assigned to the Powder Technology Section of TRW Materials Technology under Jim Fleck, Section Manager. Engineering and technician responsibilities resided with Dr. B. Lynn Ferguson and John C. Arnold, respectively. Mr. Frank T. Lally, Consultant, provided support in the area of tool design.

SUMMARY

The goal of this program was to develop a cost effective production process to isothermally forge the final drive pinion of the M60 tank. The forging would be near-net shape with only tooth shaving or grinding remaining necessary to finish the tooth. Low alloy steel powder, water atomized 4600 prealloyed powder, was used. Mechanical property levels suitable for application of such forgings must be demonstrated.

The end results of the program can be summarized as follows:

1. Isothermal forging trials on test coupons had successfully demonstrated that die fill and densification were complete when a preheat temperature of 1650F (900C), a pressure of 10 tsi (140 MPa) and a dwell time of 15 minutes were used. Toughness and ductility for the pieces were equivalent to that of conventionally forged 4600 grade parts.

2. A minimum deformation preform must be used, as the poor lubrication, low forging pressure, and the well sintered microstructure combine to reduce metal flow in this creep type deformation.

3. A novel die manufacturing method was used to guarantee accurate registry of the forging die cavity and the gear shaped punch. The top punch was cut from a casting by wire EDM using NC technology. The tape was corrected for electrode overburn and desired clearance gap, and electrodes for die sinking were then cut.

4. The program was unsuccessful in demonstrating the primary goal. Due to lubrication/die release problems, no successful forgings were made. Parts could not be ejected from the die. An initial trial done at a low load had indicated possible success, but full load trials were not extractable from the die. Changes in die design offer possible solutions to this problem.

Isothermal forging of steel powder preforms is not yet a production process. Once the die release problem is solved, isothermal forging can be selectively applied as a cost reduction process where part configuration and/or press capacity considerations rule out conventional forging.

I. INTRODUCTION

Powder metal (P/M) forging of low alloy steels has been shown to be a cost effective manufacturing process with net or near-net shape capability [1-3]. Both axisymmetric and asymmetric parts have been forged successfully on Army-sponsored programs utilizing 4600 grade steel powder to produce high performance parts. The conventional P/M forging process consists of:

- Cold press a compact
- Sinter
- Hot forge for die fill and densification.

Typical compaction pressures are 30 to 40 tsi (410 to 550 MPa) and forging pressures are 30 to 70 tsi (410 to 965 MPa). This means that the maximum forgeable plan area is limited by the press capacity. Values in Table I for conventional press sizes indicate the maximum allowable plan areas for conditions of 30 tsi (410 MPa) compaction pressure and 40 tsi (550 MPa) hot forging pressure, which represent normal P/M working pressures.

TABLE I-1

Maximum Plan Areas for P/M Forging

Press Capacity	Compact Plan Area*	Forging Plan Area**
150 Tons (1.3 MN)	5 in^2 (.003 m^2)	3.8 in^2 (.002 m^2)
500 Tons (4.4 MN)	16.7 in^2(.001 m^2)	12.5 in^2 (.008 m^2)
750 Tons (6.7 MN)	25 in^2 (.016 m^2)	18.8 in^2 (.012 m^2)
1000 Tons (8.9 MN)	33.3 in^2 (.021 m^2)	25 in^2 (.016 m^2)
1500 Tons (13.3 MN)	50 in^2 (.032 m^2)	37.5 in^2 (.024 m^2)
2000 Tons (17.8 MN)	66.7 in^2 (.043 m^2)	50 in^2 (.032 m^2)
3000 Tons (26.7 MN)	100 in^2 (.065 m^2)	75 in^2 (.048 m^2)

* 30 tsi (410 MPa) Pressure

** 40 tsi (550 MPa) Pressure

Isothermal forging technology offers the potential to forge complex shapes with large plan areas to near-net shape utilizing low forging pressures. A

machine gun cover plate for the .50 caliber M85 machine gun with a plan area of 35 in^2 (.023 m^2) was isothermally forged successfully to full density and complete die fill at a pressure of 10 tsi (138 MPa). This technology allows parts with significantly larger plan areas to be forged on existing equipment.

Tanks contain a variety of parts with large plan areas (15 in^2 to 300 in^2 (.010 m^2 to .18 m^2)) that are candidates for P/M application. Two such parts are the final drive gear (P/N 19207-7364141) and the mating pinion gear (P/N 19207-7364142. Contract DAAK30-78-C-0029 was issued by the U. S. Army Tank Automotive Research and Development Command (TARADCOM) to develop an isothermal forging process routing for manufacturing the pinion gear (plan area 13.5 in^2 (.009 m^2). Variables developed during this program would then be applied to a follow-on program to isothermally forge the final drive gear having a plan area of ~260 in^2 (.17 m^2).

This final report contains the results of an isothermal forging program designed to produce the pinion gear (P/N 19207-7364142) to near-net shape using prealloyed 4600 steel powder as the starting material.

2.0 POWDER CHARACTERIZATION

2.1 Powder Procurement

Commercially available powders were purchased for this study. The powder grades and vendors are contained in Table 2-1.

TABLE 2-1

Starting Powders and Their Source

Powder Grade	Type	Vendor
Ancorsteel 4600	Water Atomized Prealloyed Steel Powder	Hoeganaes Corporation
4600	" " " " "	A. O. Smith
4800	" " " " "	Pfizer, Inc.
AN-325 Ni	" " Nickel Powder	Glidden Metals, Div. of SCM Corporation
G.P. 280	Powdered Graphite	Graphite Products Corp.
Grade 1651 Graphite	Microcrystalline Flake Graphite	Southwestern Graphite Company

2.2 Powder Characterization

2.2.1 Grade 4600 Steel Powder

Grade 4600 steel powder is a water atomized prealloyed Ni-Mo steel of the chemistry range given in Table 2-2. The chemistries of the starting powders are included in this table. Both powder chemistries fall within the aim chemistry for 4600 grade.

The powder from both vendors arrived in barrels containing 500 lbs. (227 Kg) of powder each. Chemistry sampling revealed no chemistry variations between barrels or within barrels for each vendor. Of concern was the possibility of particle size segregation within a barrel caused by particle movement during shipping. Sieve analyses for powders from both vendors as a function of location are given in Table 2-3. No significant particle size variations are observed, indicating that blending of the powder in each barrel could be eliminated since an arbitrary sample of powder would approximate the batch characteristics.

TABLE 2-2

4600 Steel Powder Chemistries

Element	Aim Chemistry*(%)	A. O. Smith Powder TRW Analysis (%)	A. O. Smith Powder Vendor Analysis (%)	Hoeganaes Powder TRW Analysis
C	≤0.01	-	-	-
Mn	0.15/0.30	0.27	0.31	0.26
Si	≤0.35	0.18	-	0.15
P	<0.04	0.018	-	0.019
S	<0.04	0.040	0.041	0.021
Ni	1.65/2.00	1.81	1.79	1.75
Mo	0.4/0.6	0.56	0.57	0.43
Cr,Cu,Al	-	-	-	-
O	-	-	0.28	-
Fe	Bal.	Bal.	Bal.	Bal.

* Powder Specifications Are Not Standardized

Typical particles are shown in Figures 2-1 and 2-2 for these powders. The particles are irregular in shape which is indicative of water atomized powder. Polished and etched cross sections in parts (a) and (b) of Figure 2-2 show that grain size is not dependent on particle size for these powders, and the grain shape is equiaxed.

The physical properties of the powder are important for processing and design considerations. Apparent density tells the parts maker how much powder can be poured into a given volume. Tap density indicates the densification capability of vibration or jolting on the loose powder. These data are important for compaction tooling design. Green strength and green density for steels are measured at the normal 30 tsi (414 MPa) compaction pressure. Comparison of the green density and sintered density indicates the dimensional stability of the compact during sintering. Values for the properties are given in Table 2-4. These data show that the irregular particle shape results in low apparent and tap densities, which amount to only 39% and 52% of theoretical density respectively. For the sintering conditions indicated in the table, the compacts have good stability during sintering.

TABLE 2-3

Sieve Analysis* of Starting 4600 Steel Powder

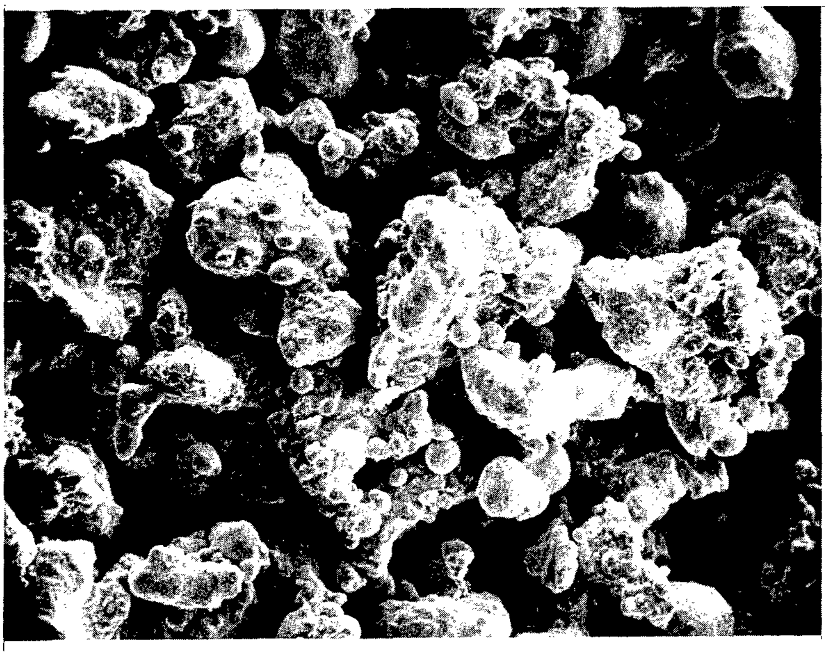
A. O. Smith Powder

Vendor Analysis Mesh		Mesh	Barrel 1 Top	Barrel 1 Middle	Barrel 1 Bottom	Barrel 2 Top	Barrel 2 Middle	Barrel 2 Bottom
-48+60	0.6							
-60+80	2.7	+80	6.8	4.9	5.1	9.4	6.5	6.9
-80+100	2.3	-80+100	10.0	7.7	8.0	15.6	8.1	8.2
-100+150	14.7	-100+150	19.1	16.2	16.8	13.5	16.6	17.9
-150+200	19.8	-150+200	19.3	17.6	16.9	33.6	16.6	17.8
-200+250	5.6	-200+250	7.4	5.9	5.2	5.6	7.3	7.2
-250+325	18.0	-250+325	18.0	21.7	22.9	13.3	22.6	19.4
-325	26.3	-325	17.2	25.1	23.2	8.1	20.6	22.0

Hoeganaes Powder

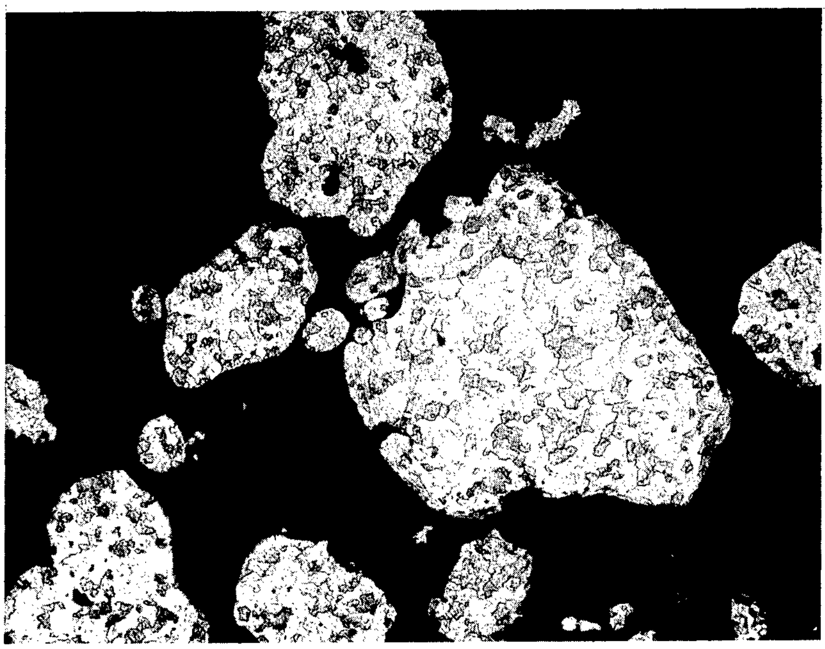
Mesh	Barrel 1 Top	Barrel 1 Middle	Barrel 1 Bottom	Barrel 2 Top	Barrel 2 Middle	Barrel 2 Bottom
+80	4.4	3.1	3.3	3.5	2.9	5.3
-80+100	12.9	9.2	11.8	11.3	10.4	12.4
-100+150	24.3	17.6	26.0	21.0	22.5	20.0
-150+200	20.3	20.1	18.3	18.2	15.8	27.4
-200+250	8.3	8.1	9.0	8.3	8.4	9.2
-250+325	16.5	21.4	16.0	22.3	22.1	15.5
-325	11.9	18.4	13.6	15.2	18.7	9.0

* Numbers Refer to Weight Percents.

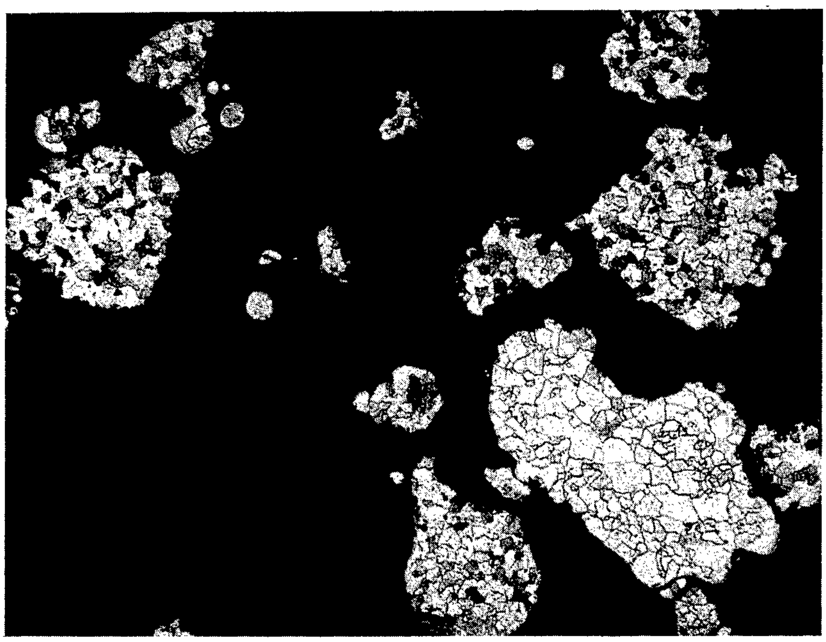


200X

Figure 2-1. SEM Photomicrograph of 4600 Steel Powder (A. O. Smith-Vendor) Showing the Irregular Particle Shape.



(a) 4600 - A. O. Smith - Vendor



(b) 4600 - Hoeganaes Corp. - Vendor

Figure 2-2. Light Photomicrographs of Polished and Etched Powder Particles Revealing the Fine Grain Structure. Magnification is 200X and Etchant is Nital.

TABLE 2-4

Physical Properties of 4600 Steel Powder

	A. O. Smith Data	TRW Data
Apparent Density - gr/cc	3.1	3.4
Tap Density - gr/cc	-	4.1
Green Density - gr/cc*	6.42	-
Green Strength - psi*	5.10	-
Sintered Density - gr/cc	-	6.5

* Compressed at 30 tsi (414 MPa) with 0.75% Zinc Stearate Added.
** 2200F (1204C) in H_2 for 1 Hour.

2.2.2 Grade 4800 Steel Powder

Grade 4800 steel powder can be processed by blending nickel powder with Grade 4600 powder or as completely prealloyed powder. Prealloyed powder made by water atomization was purchased from Pfizer. The chemical analysis of this powder as determined by the vendor and TRW is contained in Table 2-5.

TABLE 2-5

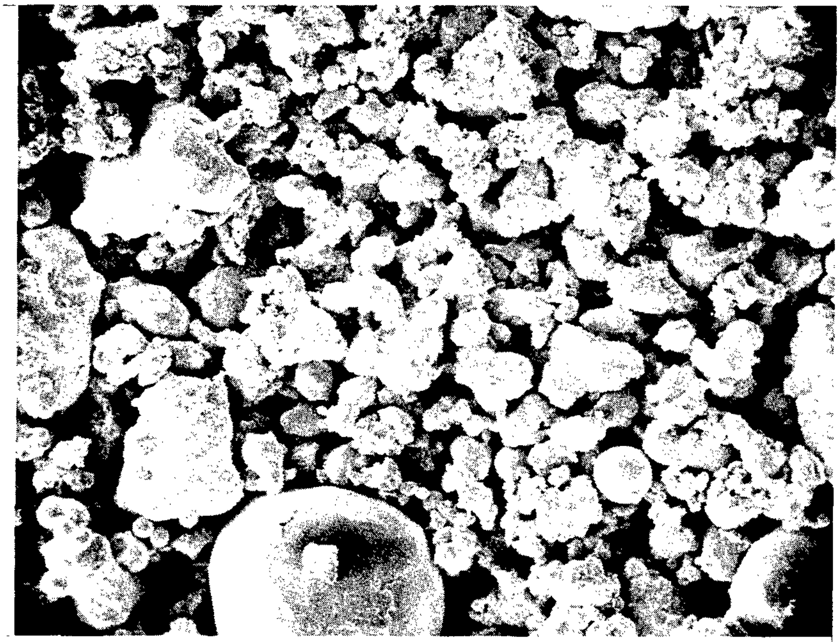
Chemical Analysis of Pfizer 4800 Steel Powder*

Element	Vendor Analysis	TRW Analysis
C	0.06	-
Mn	0.17	0.15
Si	0.12	0.14
P	-	-
S	-	-
Ni	3.79	3.57
Mo	0.60	0.60
Cr	0.11	0.14
Cu	-	-
Al	-	0.03
O	-	0.280
Fe	Bal.	Bal.

* Numbers Refer to Weight Percents

A point to note concerning this chemistry is the very high initial oxygen content.

Several characteristics are evident concerning this powder. First the particle size is very fine. Sieve analysis in Table 2-6 shows that the majority of particles are -250 mesh in size. High oxygen levels and fine particle size usually go hand-in-hand since oxygen content reflects particle surface oxide content. Second, the particle shape as shown in Figure 2-3 is more spherical than that of the 4600 powder. Also, Figure 2-3 shows the presence of several large spherical particles in the 100 to 300μ size (150μ = 100 mesh powder). The extreme percentage of fines, the high oxygen content and the near spherical shape are indications of lack of process control during atomization.



100X

Figure 2-3. SEM Photomicrograph of 4800 Steel Powder Showing A Large Fraction of Fine Particles and A Small Fraction of Large Spherical Particles.

TABLE 2-6

Sieve Analysis* of Pfizer 4800 Steel Powder

Vendor Analysis		TRW Analysis			
Mesh		Mesh	Top	Middle	Bottom
+120	2.1	+80	Trace	0.1	Trace
-120+140	5.0	- 80+100	0.3	0.2	2.2
-140+200	6.0	-100+150	9.1	8.9	6.3
-200+270	23.9	-150+200	28.6	19.1	16.4
-270+325	7.1	-200+250	13.4	11.6	-
-325	44.7	-250+325	35.2	32.9	28.1
		-325	12.0	27.9	45.2

* Numbers Refer to Weight Percent

2.2.3 Nickel Powder

Since Grade 4800 can be achieved by making nickel additions to 4600 pre-alloyed powder, nickel powder was procured. Normally elemental nickel powder is produced by grinding, by electrolytic reaction or by melt-atomization techniques. The powder supplied by Glidden Metals was atomized powder. The chemical composition of the powder is given in Table 2-7 and shows that the powder is essentially elemental nickel. The sieve analysis in Table 2-8 shows that the bulk of the powder is -325 mesh as ordered. This fine size was ordered to aid homogenization. A result of the water atomization is the irregular particle shape shown in Figure 2-4. Polished cross sections of particles reveal in Figure 2-5 that each particle is comprised of many equiaxed grains.

TABLE 2-7

Chemical Analysis* of AN-325 Nickel Powder

C	Si	Co	Fe	B	Cu	Ni
0.026	0.35	0.06	0.26	<0.01	0.08	88.1

* Numbers Refer to Weight Percents

TABLE 2-8

Sieve Analysis* of Nickel Powder

Vendor Analysis		TRW Analysis	
Mesh		Mesh	
+200	-	+250	Trace
-200+325	4.6%	-250+325	43.0%
-325	95.4%	-325	56.4%

* Numbers Refer to Weight Percents.

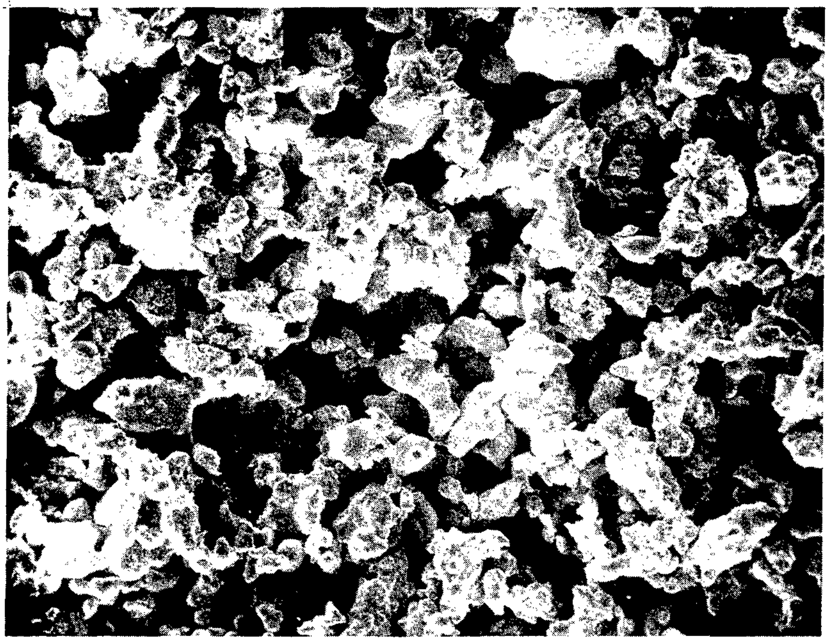
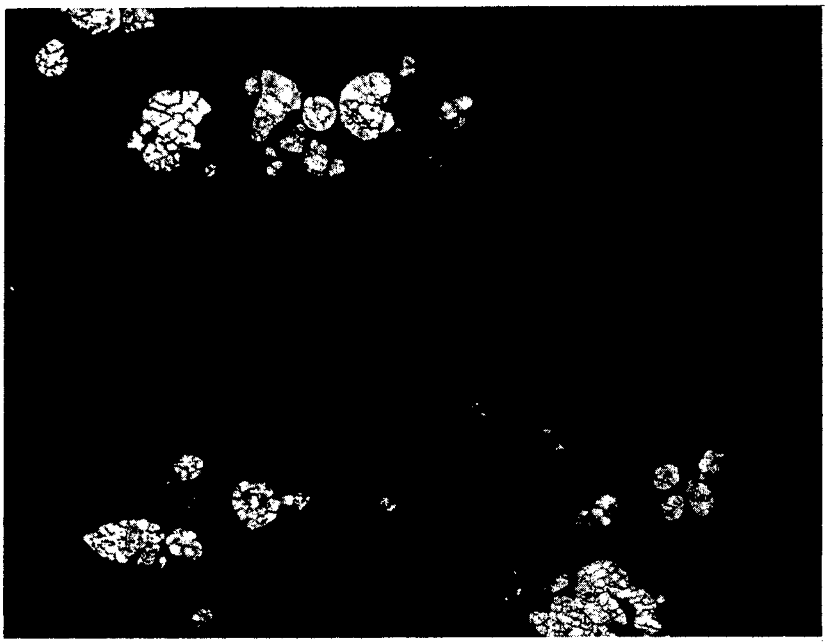


Figure 2-4   SEM Photomicrograph of Nickel Powder (200X).



200X

Figure 2-5. Polished and Etched Cross Section of Nickel Powder Particles.

3.0 ISOTHERMAL FORGING OF P/M STEELS - PROCESS DEVELOPMENT

To investigate the effect of process variables on mechanical properties, a series of test coupons were isothermally forged. This process development step allowed the effects of preform geometry, preform coating and load dwell time to be determined for tensile and impact properties. At the same time a qualitative feel for surface finish, die fill and ejection loads could be developed.

3.1 Preform Fabrication

Powder mixtures of the following compositions were prepared by blending the appropriate powders for 20 minutes in a V-cone blender in 20 Kg batches:

- A4600 + 0.27% graphite + 0.75% zinc stearate
- A4600 + 2.0w/o AN325 Ni + 0.27% graphite + 0.75% zinc stearate
- 4800 + 0.27% graphite + 0.75% zinc stearate.

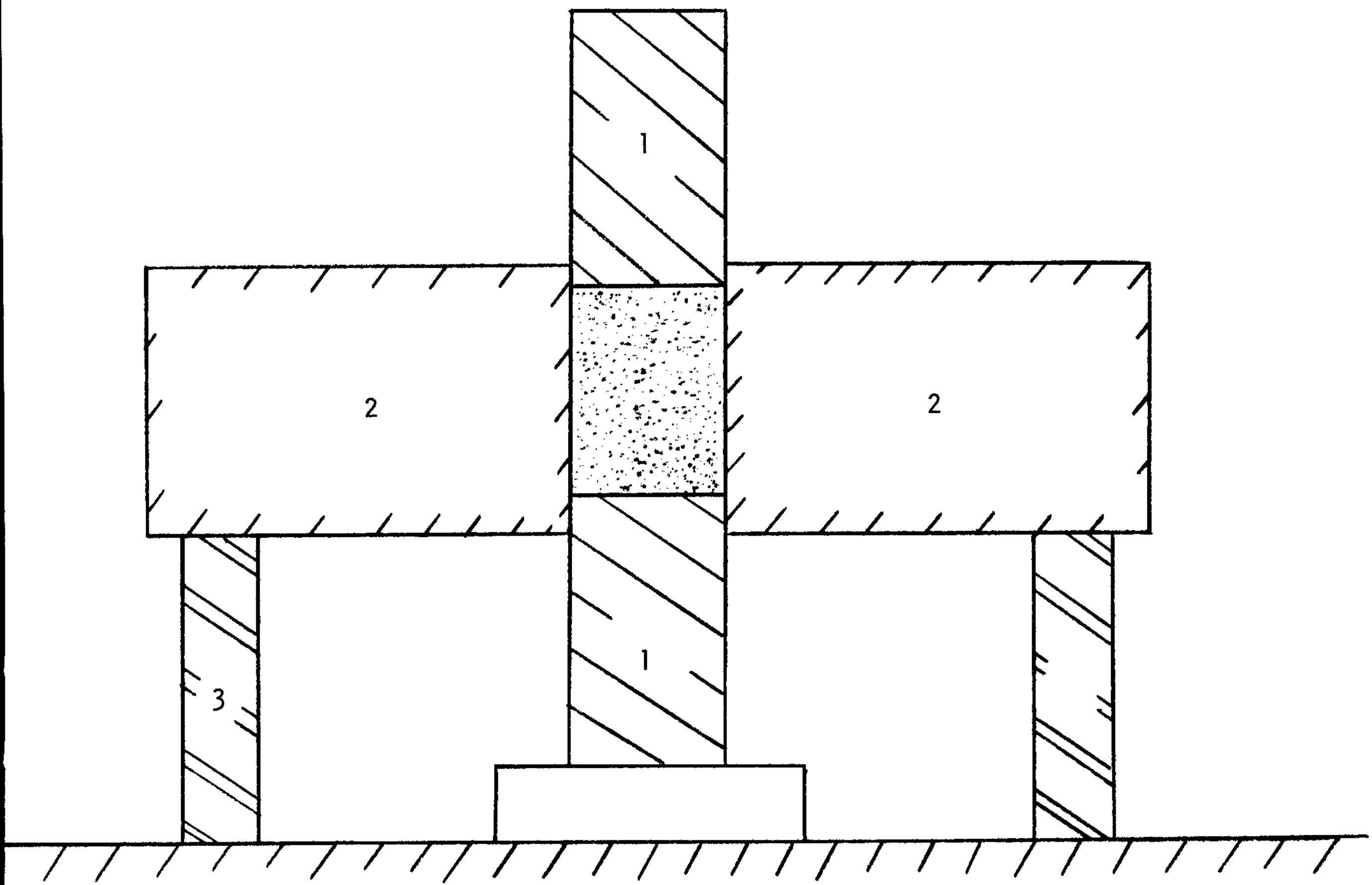
In later batches the admixed zinc stearate lubricant was eliminated from the blended powders.

3.1.1 Compacts of 1.95" W x 3.95" L x 1.25" H (0.050m x 0.100m x 0.032m) were cold pressed in hardened tool steel dies at 30 tsi (414 MPa). A die wall lubricant of zinc stearate was applied by brushing an alcohol base slurry on the die walls and punch faces and air drying. A schematic of the compaction tooling is shown in Figure 3-1. This punch-ring die combination approximates a floating die system.

Because of the high percentage of fines, the 4800 + graphite blend could not be compacted without the presence of ejection cracks. By removing about 50% of the fines, compacts were successfully hard die pressed.

3.1.2 Compacts were batch sintered in an NRC vacuum induction furnace that had been modified to accept a controlled atmosphere. The coupons were heated to ~1200F (650C), held for 15 minutes to allow lubricant burnoff, and then were heated to 2200F (1204C). They were held at this temperature for one hour, and were then furnace cooled. The incoming atmosphere was a mixture of dry H_2 gas and 1-2 volume percent CH_4. Argon was used to purge the chamber prior to heatup and after the chamber had dropped below 1000F (540C) during cooldown.

Previous work had shown that the above conditions would result in the necessary achievement of <300 ppm of oxygen remaining in the powder and the appropriate carbon level of 0.20%[1-4]. Because of the high initial oxygen contents of the A. O. Smith 4600 powder (~2800 ppm) and the Pfizer 4800 powder (>2800 ppm), there was concern about the ability to reduce oxygen to the needed levels. Chemical analysis of



1 - Punches

2 - Ring Die

3 - Standards

Figure 3-1. Test Coupon Preform Compaction Tooling.

sintered pieces showed that the 4600 powder could be reduced to <300 ppm of oxygen using the above procedure, but the 4800 powder could not be reduced in oxygen content to these levels. Sample chemistries are given in Table 3-1 for various powder-graphite blends and sintering runs. Also, these sintering conditions did not produce a homogeneous microstructure in the 4600+ 2% Ni chemistry so that an additional 2 hour-2200F (1204C) heat treatment was required for this grade.

TABLE 3-1

Effect of Sintering* on Oxygen and Carbon Levels in Steel P/M Preforms

Powder	% C	O_2 (ppm)
4600 + 0.28% Graphite	0.17	140
4800 + 0.30% Graphite	0.15	1900
4600 + 2% Ni + 0.28% Graphite	0.18	140

* Sintering Conditions: 2200F (1204C) for 1 Hr in H_2+CH_4.

The product of this operation was a minimum deformation type of preform. To examine the effect of forging deformation level on properties, several of the preforms had 1 inch (.025m) removed from their lengths. Placement of such preforms on their sides in the die would allow lateral metal flow (upsetting) to occur during forging. Transverse flow (side forging) could be accommodated by simply placing a minimum deformation type preform on its side in the die. Figure 3-2 shows the geometry and orientation of the minimum deformation (repress) preform, the side forge preform and the upset preform with the final forging.

3.2 Preform Coating

The sintered preforms were then coated with one of a variety of lubricants. The preforms were warmed to ∿100F (40C) and the coating was applied by brushing a slurry onto the warmed surfaces and allowing it to dry. The lubricants examined were:

- Graphite in water
- TiO Form LF22*
- TiO Form LF22 + CRT (11:1 and 22:1 ratios)
- CRT** + graphite in xylene.

These coatings were qualitatively evaluated for resistance to burnoff during preheating, aid in ejection, surface finish and buildup in die.

* LF is a silicone binder + graphite in xylene.

** CRT is boro-silicate frit and boric acid in an aromatic solvent.

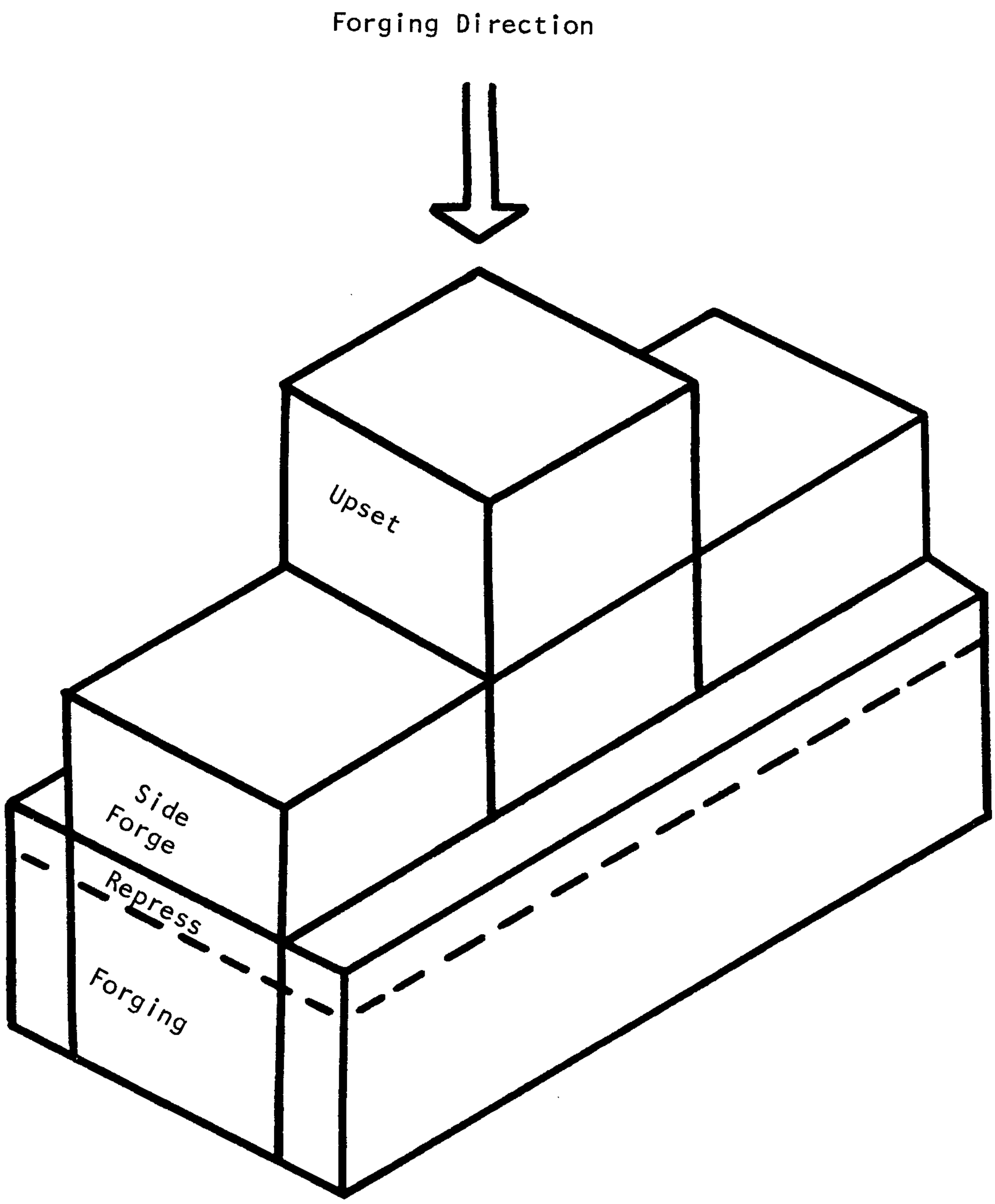


Figure 3-2. Schematic of the Isothermally Forged Test Coupons from 4620 Steel P/M Preforms.

3.3 Isothermal Forging of Test Coupons

A ring die and punch set of cast IN 100 were used to isothermally forge test coupons with plan dimensions of 2.0 inch width (.051m) and 4.0 inch length (.102m). The die is heated by induction as indicated, and ejection of the forge part is performed by action of a hydraulic cylinder on the bottom punch.

3.3.1 First Trial

For the first trial, the following cycle was to be used:

- Preheat forging die set to 1650F.
- Preheat coated preform at 1650F (900C) for 10 minutes in hydrogen.
- Transfer preform to die set and apply a pressure of 2 to 3 tsi (14-21 MPa) until the temperature restabilizes.
- Apply full pressure of 10 tsi (138 MPa) for 5, 10 or 15 minutes dwell times.
- Eject and oil quench the forged coupon.

Three coatings were examined in this trial, viz., graphite and the two LF 22 + CRT compositions. For these conditions, the graphite coating resulted in sticking in the die cavity as the lubricant partially burned off during preheating. Pieces with the LF 22 + CRT coatings were forged successfully, although glass buildup in the die and on the punches was a problem. Ejection was difficult and required rapid expansion of the die away from the part for success.

Using the 11:1 mixture of LF 22 + CRT coating, minimum deformation preforms were forged isothermally at 5, 10 and 15 minute dwell times. Complete die fill was achieved only for the 15 minute dwell time. Bulk densities of >98% of theoretical were measured for each dwell condition.

A set of forgings with 4620 composition using a 15 minute dwell cycle was processed for property evaluation. Low hardness values and wide scatter in hardness data during heat treat trials indicated possible carbon control or density problems. Chemical analysis reports showed the carbon level to be correct. Metallographic examination of polished cross sections revealed porosity. It was felt that this porosity was the result of a short preheat or of too low a forging load. No further testing was performed on these pieces.

3.3.2 Second Trial

A second isothermal forging trial was conducted with 4620 receiving major emphasis. The 4800 and 4600 + 2 w/o Ni compositions were examined but at a low priority level at this stage of the program. The isothermal forging conditions were:

- preheat die to 1650F (900C).
- preheat coated preform to 1650F (900C) for 20 minutes in hydrogen.
- transfer preform to die set and immediately apply the full pressure of 10 tsi (138 MPa).
- after the temperature stabilizes at 1650F, dwell for 5 or 15 minutes.
- eject and oil quench the part.

For this trial, LF-22, LF-22 plus CRT and CRT plus graphite coatings were examined. Of these coatings LF-22 gave the best surface finish at no increase in ejection difficulty. The CRT glass-containing coatings led to buildup in the die cavity. In all cases ejection was difficult, but could be best accomplished by cooling the assembly to ∿1200F (650C) and then rapidly heating the ring die to 1650F (900C) followed by ejection. Once the piece started to move in the die, ejection progressed smoothly. The bulk of the forgings were done using LF-22 as the preform coating.

Minimum deformation, side forge and upset type preforms were isothermally forged at 10 tsi (138 MPa) after a 20 minute preheat to 1650F (900C). After transfer of the piece to the die full load was applied immediately upon die closure. Dwell times of 5 minutes (repress only) or 15 minutes began once the temperature had stabilized. For this die set, temperature stabilization under load required 3-5 minutes, depending on transfer speed. Examination of forgings showed that side forged and upset forged pieces had high density but very poor die fill due to lubrication/metal flow deficiencies. Repressed pieces with the 15 minute dwell had both high density and complete die fill. This is in line with the findings reported in Reference (3) which point out the need to limit deformation with isothermal forging if die fill is to be complete.

Because atmosphere protection is lacking during transfer from the preheat furnace to the die set, transfer time is critical as only the integrity of the preform coating provides an oxygen barrier. Forgings were therefore grouped into fast (<30 seconds) or slow (30-45 seconds) categories. If the preform took longer than 45 seconds to be loaded into the die and sealed off by insertion of the top punch, the preform was slowly cooled to ambient in sand. Several of these pieces were recoated, preheated and forged, and are referred to as repeats.

3.4 Evaluation of Isothermally Forged Test Coupons

3.4.1 Mechanical Test Sample Preparation

The quenched forgings were batch normalized at 1650F (900C) for 1 hour under a protective atmosphere of H_2 + 2% CH_4 gas. The forgings were then sectioned into tensile and Charpy V-notch (CVN) test piece slugs, heat treated and

then finish machined. Heat treatment consisted of austenitizing the specimen blanks at 1600F (870C) for one hour in an argon atmosphere followed by oil quenching. Pieces were then tempered in air for one hour at 750F (400C), 1000F (540C) or 1175F (635C), followed by rapid cooling to ambient.

The tensile test specimen is depicted in Figure 3-3. These are longitudinal specimens which means that the tensile axis is perpendicular to the original forging direction.

The CVN samples correspond to ASTM Standard E23, Type A specifications. These specimens are longitudinal, with the notch cut in the transverse direction as shown in Figure 3-4.

3.4.2 Tension Test Results

The longitudinal tensile samples were pulled at ambient temperature using a cross head speed of 0.005 in/min (1.3×10^{-4} m/min) through the yield point, followed by a cross head speed of 0.05 in/min (1.3×10^{-3} m/min) to failure. A one-inch (0.025 m) extensometer was used to accurately determine load vs. displacement. Values determined from the tests were yield strength, ultimate tensile strength, total elongation (%E) and reduction of area at fracture (RA). These values are found in Table 3-2.

Mean results for a 15 minute dwell time on minimum deformation preforms with a fast transfer time are shown in Figure 3-5. Also shown are typicel 4620 bar stock tensile data for the quenched and tempered hardness of R_c30 (5). The high ductility values are indications of both full density and low oxygen levels.

LF-22 proved to be an effective oxygen barrier at elevated temperatures as shown by the oxygen level given in Table 3-3 for typical fast and slow transfer cases and a repeat case. These data are supported by the tensile data in Figure 3-6 which compares the slow and fast transfer conditions. The strength levels of the slow transfer pieces are equal to those of c/w* bar stock and above those of the fast transfer case. Ductility values for the two conditions are equal.

Looking at the effect of metal flow on tensile properties, Figure 3-7 shows that strength is not affected. While side forging has no affect on longitudinal ductility, upsetting, which features metal flow in the tensile testing direction, results in enhanced ductility. This finding is similar to results reported for conventional P/M forging and is expected[6].

To verify the effect of dwell time, a piece was forged with a 5 minute dwell time. In Figure 3-8 one sees that strength level is not affected by dwell, but that ductility is markedly affected. This supports the earlier Trial 1 findings that 15 minutes is necessary to achieve full density.

---

* cast/wrought

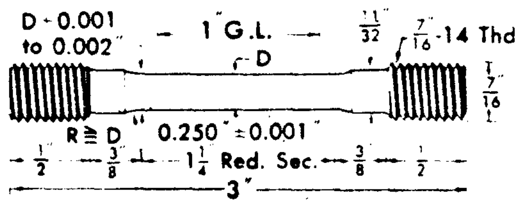


Figure 3-3. Longitudinal Tensile Specimen Geometry.

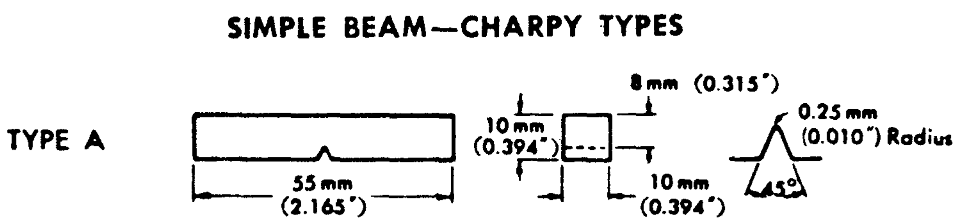


Figure 3-4. Longitudinal CVN Impact Specimen Geometry.

TABLE 3-2

Longitudinal Tensile Data for Isothermally Forged 4620 Steel Powder Preforms

Condition	Dwell	R_C	Forging #	Yield Strength KSI	Yield Strength (MPa)	Ultimate Strength KSI	Ultimate Strength (MPa)	%E	%RA
• Fast Transfer		30	102-1	87.1	(600.5)	107.2	(739.1)	14.5	43.4
• Repress Preform			102-2	85.2	(587.4)	105.9	(730.2)	14.5	43.5
• 15 Min. Dwell			103	86.2	(594.3)	106.3	(732.9)	16.0	46.1
			109	88.8	(612.3)	109.1	(752.2)	15.5	43.1
		25	110-1	74.4	(513.0)	91.8	(632.9)	26.5	59.9
			110-2	74.9	(516.4)	92.3	(636.4	26.5	60.1
			111	87.9	(606.0)	109.8	(757.0)	16.0	48.0
• Slow Transfer		30	107-1	119.4	(823.2)	132.6	(914.2)	15.0	42.8
• Repress Preform			107-2	105.9	(730.2)	121.4	(837.0)	16.0	46.9
• 15 Min. Dwell			108	107.3	(739.8)	122.4	(843.9)	12.0	40.8
		37	112-1	135.3	(932.9	165.2	(1139.0)	4.5	21.0
			112-2	148.8	(1025.9)	182.8	(1196.9)	7.0	17.4
• Repeat	5 Min.	30	118	109.1	(752.2)	121.8	(839.8	7.0	21.0
• Repress Preform	15 Min.	30	117	106.7	(739.7)	121.8	(839.8)	18.0	41.1
• Slow Transfer • Side Forged • 15 Min. Dwell		30	113	109.6	(755.7)	124.8	(860.5)	12.5	44.3
• Repeat • Upset • 15 Min. Dwell		30	119	107.9	(743.9)	122.9	(847.4)	20.0	57.1
			120	109.0	(751.5)	122.8	(846.7)	18.0	57.6

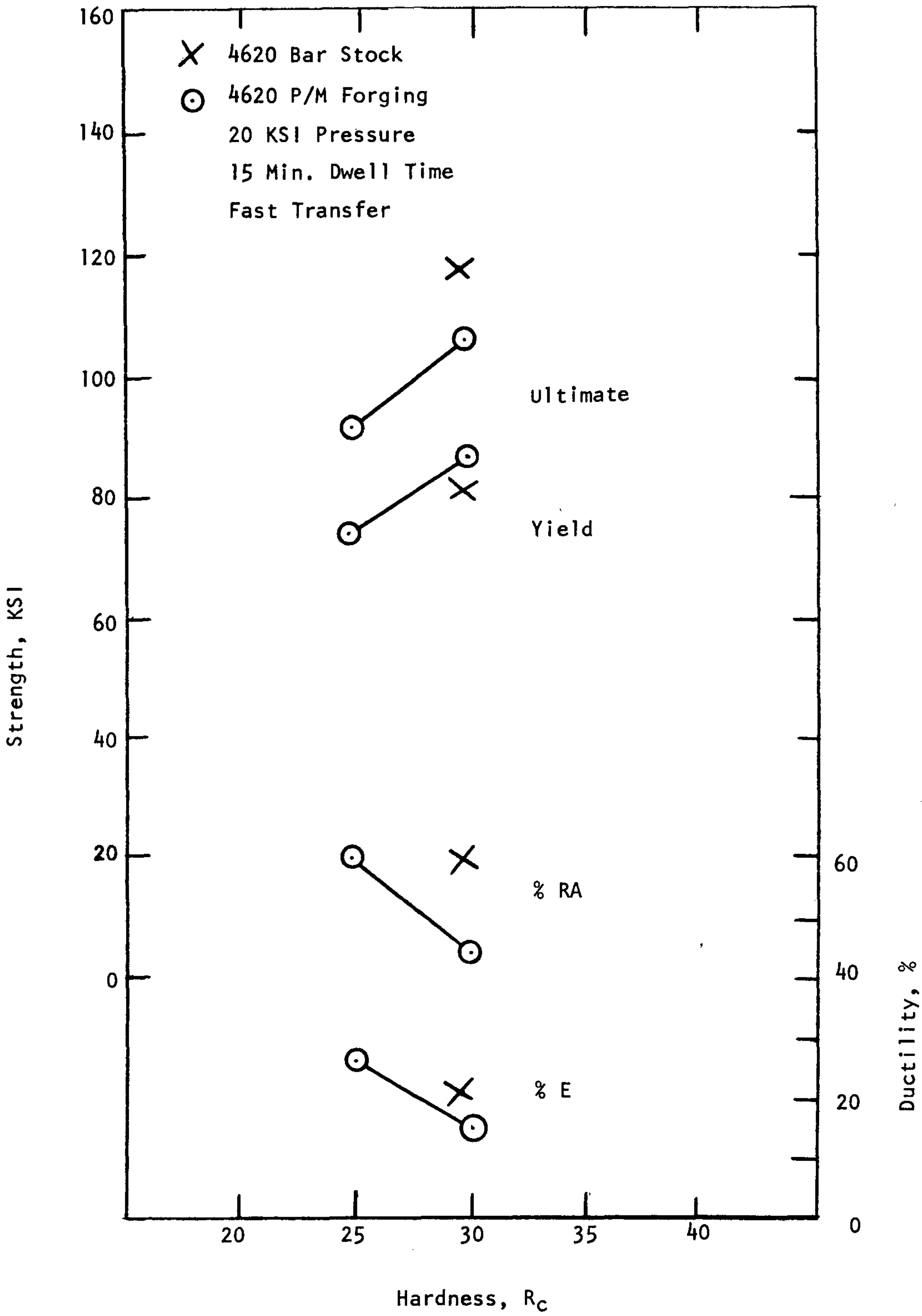


Figure 3-5. Tensile Properties of Isothermally Forged 4620 P/M Test Coupons.

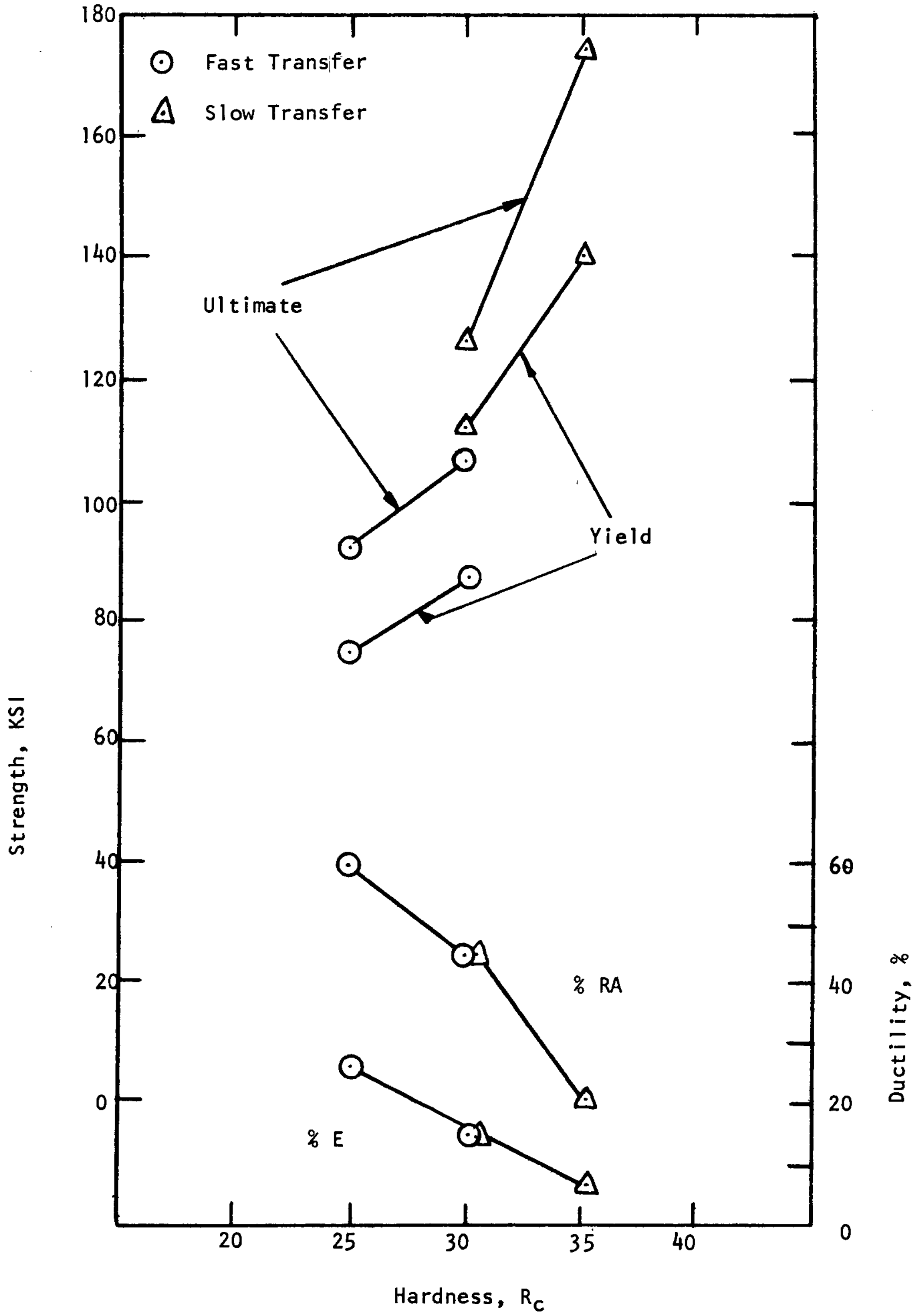


Figure 3-6. Effect of Preform Transfer Speed from Preheat Furnace to Die on Tensile Properties of Isothermally Forged 4620 P/M Test Coupons.

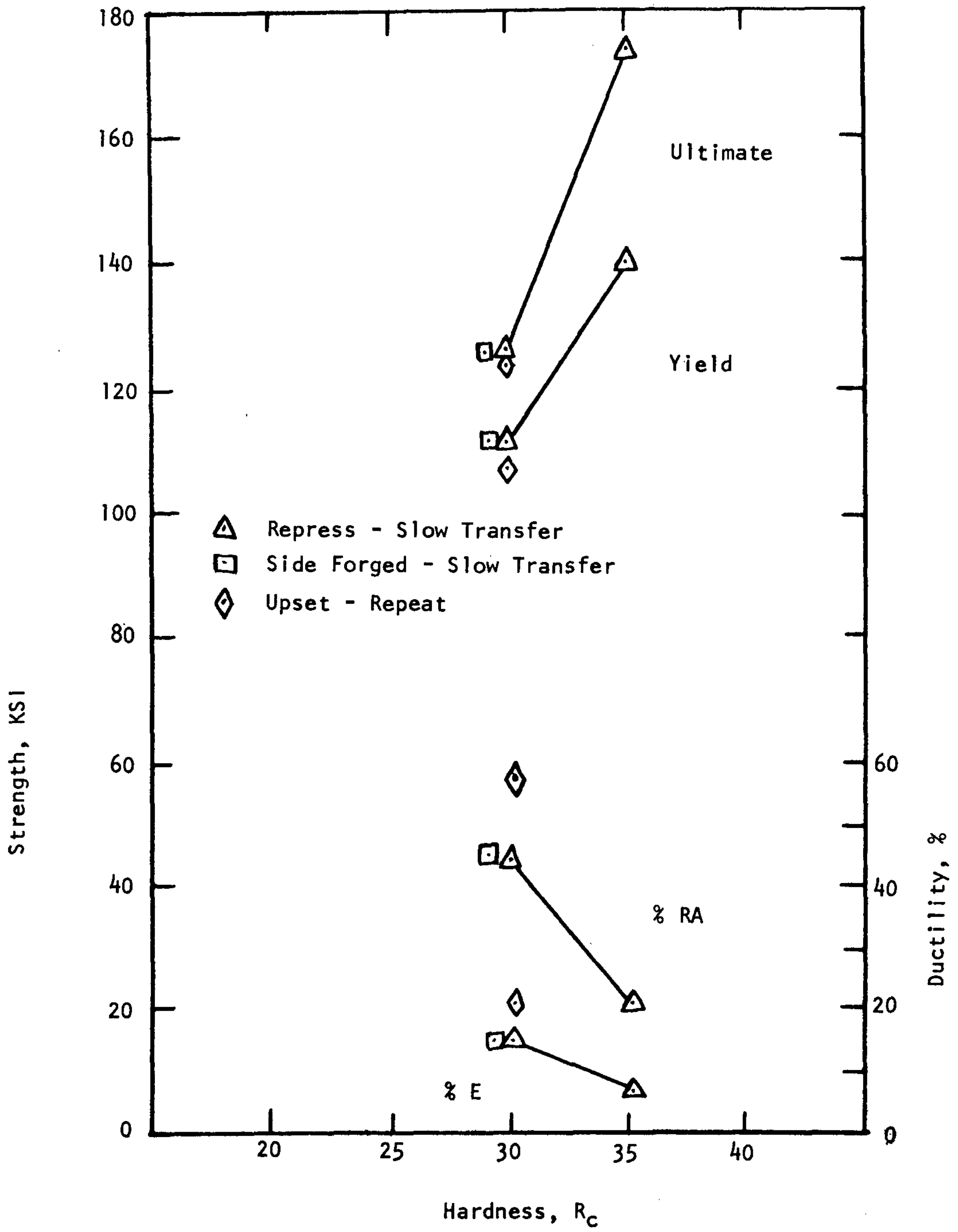


Figure 3-7. Effect of Metal Flow on Tensile Properties of Isothermally Forged 4620 P/M Test Coupons.

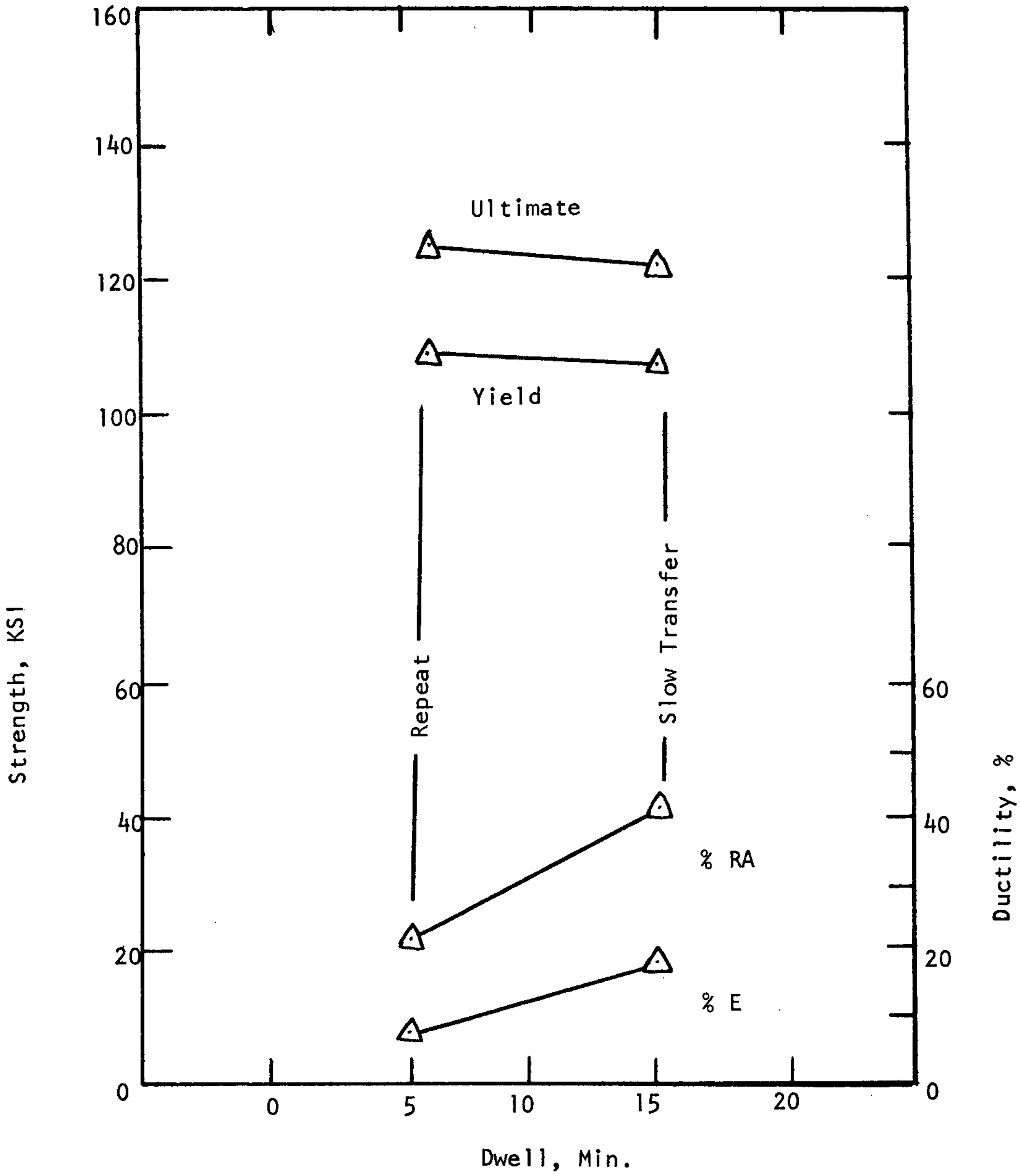


Figure 3-8. Effect of Load Dwell Time on the Tensile Properties of Isothermally Forged 4620 P/M Test Coupons (R_c 30).

TABLE 3-3

Oxygen Analysis of Isothermally Forged 4620 P/M Test Coupons

Condition	Oxygen Level (ppm)
Forged - Fast Transfer To Die	140
Forged - Slow Transfer to Die	140
Forged - Repeat Case	230

3.4.3 CVN Impact Test Results

The raw CVN impact data are given in Table 3-4. For purposes of comparison, the data are graphically displayed in Figures 3-9 to 3-11.

Impact data for the fast transfer condition shows in Figure 3-9 that the upper shelf energy is a function of strength or hardness level. The energy absorbed levels are somewhat lower than some of the previously published toughness data, but the fracture surface exhibits conventional ductile rupture. Shear lip development is slight. At the R_c 30 hardness level, ductile fracture is dominant at temperatures $\geq$ -40F (-40C).

Slow transfer did not affect toughness, just as it did not affect tensile ductility, as shown in Figure 3-10. Toughness of the repeat case is comparable to that of the fast transfer case. Because oxygen level and shelf energy are closely related, this finding supports the finding that LF-22 is an effective oxygen barrier for these conditions.

One sure method of increasing toughness is to incorproate metal flow into the forging. In Figure 3-11 one sees that upset forging gives the highest toughness level, and that side forging also enhances toughness over the level attained by repressing.

Dwell time affects toughness just as it does tensile ductility. Data in Table 3-4 shows that for a R_c30 hardness level, a 5 minute dwell time produces a toughness level in the range 10-11 ft. lbs. (13.6-15.0J), while the level of the 15 minute dwell cycle is 20-23 ft. lbs. (27.1-31.2J). These data illustrate the extreme effect of residual porosity on toughness, as both the 5 and 15 minute dwell times produced* bulk densities >98.5%. Comparison of impact fracture surfaces in Figure 3-12 shows that typical ductile rupture is the dominant feature on both surfaces. Some relatively flat areas are present in both that allude to prior-particle boundary failure. Generally, the piece with the 15 minute dwell time has more dimples per unit fracture area than the 5 minute piece, which is in agreement with the higher toughness value. These statements are based solely on qualitative assessment of the fracture surfaces.

TABLE 3-4

CVN Impact Data for 4620 P/M Isothermally Forged Test Coupons

Condition	R_C	Forging #	Test Temperature (°F)	(°C)	CVN Impact Value Ft/Lbs	(J)
Fast Transfer	30	102	-300	(-184)	3.0	(4.1)
Repress Preform	"	109B	-100	(- 73)	13.0	(17.6)
15 Min. Dwell	"	109A	- 40	(- 40)	10.0	(13.6)
	"	106C	- 40	(- 40)	14.0	(19.0)
	"	106A	0	(- 18)	17.0	(23.1)
	"	106B	0	(- 18)	16.5	(22.4)
	"	101A	70	(21)	21.5	(29.2)
	"	101B	70	(21)	13.5	(18.3)
	"	103A	200	(93)	15.0	(20.3
	25	111B	-100	(- 73)	12.5	(17.0)
	"	115C	- 40	(- 40)	19.5	(26.4)
	"	110	0	(- 18)	28.5	(38.6
	"	115B	0	(- 18)	16.0	(21.7)
	"	104A	70	(21)	34.5	(46.8)
	"	104B	70	(21)	35.0	(47.5)
	"	104C	200	(93)	37.5	(50.9)
	"	115C	200	(93)	18.5	(25.1)
	34	105A	70	(21)	22.0	(29.8)
	"	105B	70	(")	22.5	(30.5)
	"	105C	70	(")	14.0	(19.0)
	37	114A	70	(21)	9.0	(12.2)
	"	114B	70	(")	10.5	(14.2)
	"	114C	70	(")	11.0	(14.9)
Slow Transfer	30	107	70	(21)	20.0	(27.1)
Repress Preform	"	108A	70	(21)	17.5	(23.7)
15-Minute Dwell	"	108B	70	(")	15.0	(20.3)
	37	112	70	(21)	11.0	(14.9)
	"	116A	70	(")	7.5	(10.2)
	"	116B	70	(")	13.0	(17.6)
Dwell						
Repeat 5 Min.	30	117A	70	(21)	11.0	(14.9)
Repress	"	117B	70	(21)	10.0	(13.6)
15 Min.	30	118A	70	(")	20.0	(27.1)
	"	118B	70	(")	23.5	(31.9)
Slow Transfer	30	113A	70	(21)	34.0	(46.1)
Side Forged	"	113B	70	(")	27.0	(36.6)
15 Minute Dwell						
Repeat	30	119A	70	(21)	35.5	(48.1)
Upset Forged	"	119B	70	(")	33.5	(45.4)
15 Minute Dwell	"	120A	200	(93)	26.0	(35.3)
	"	120B	200	(93)	38.5	(52.2)

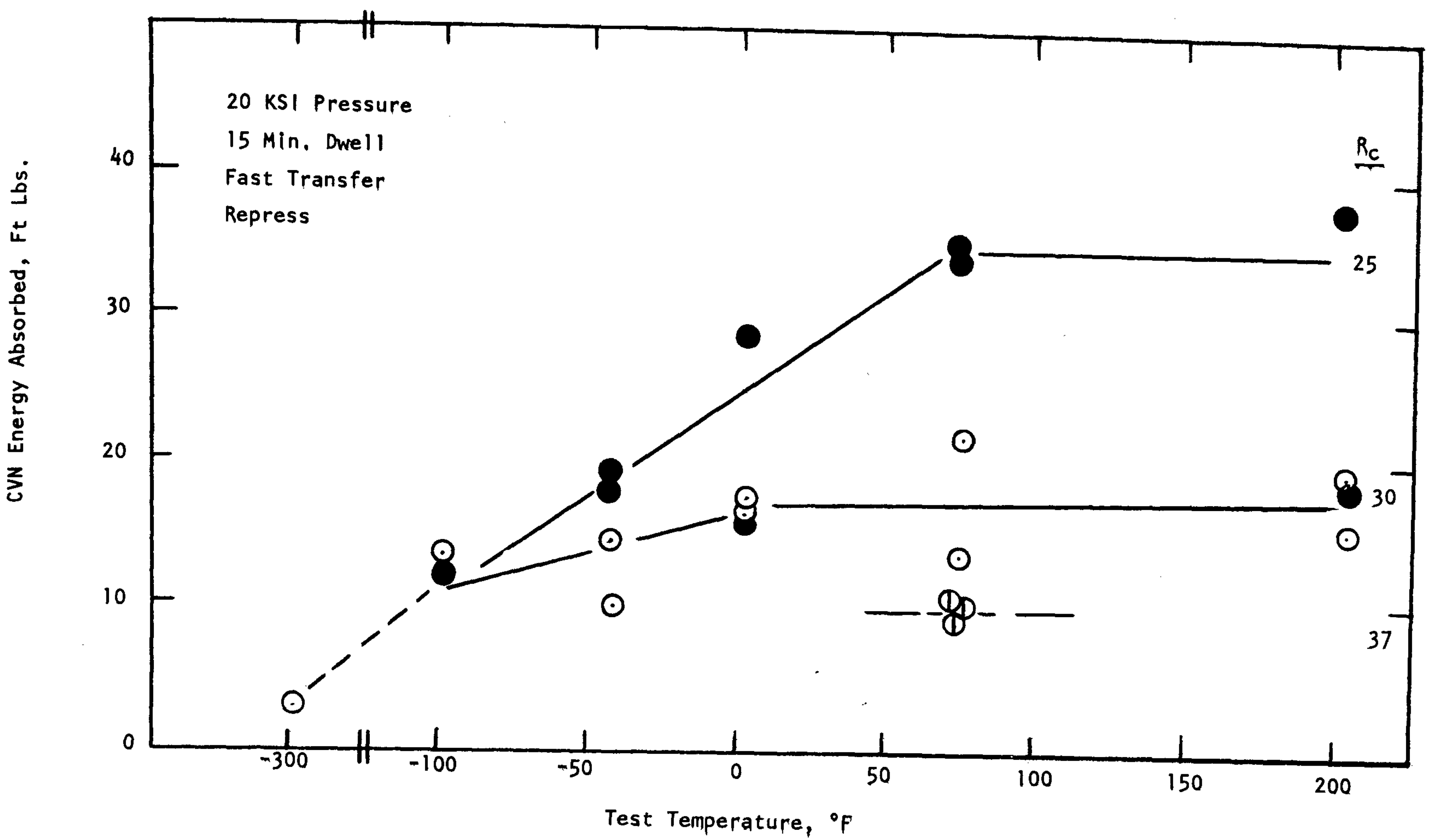


Figure 3-9. Toughness of Isothermally Forged 4620 P/M Test Coupons. Data are for Hardness Levels of R_c 25(●), R_c 30(⊙), R_c 37(⦶).

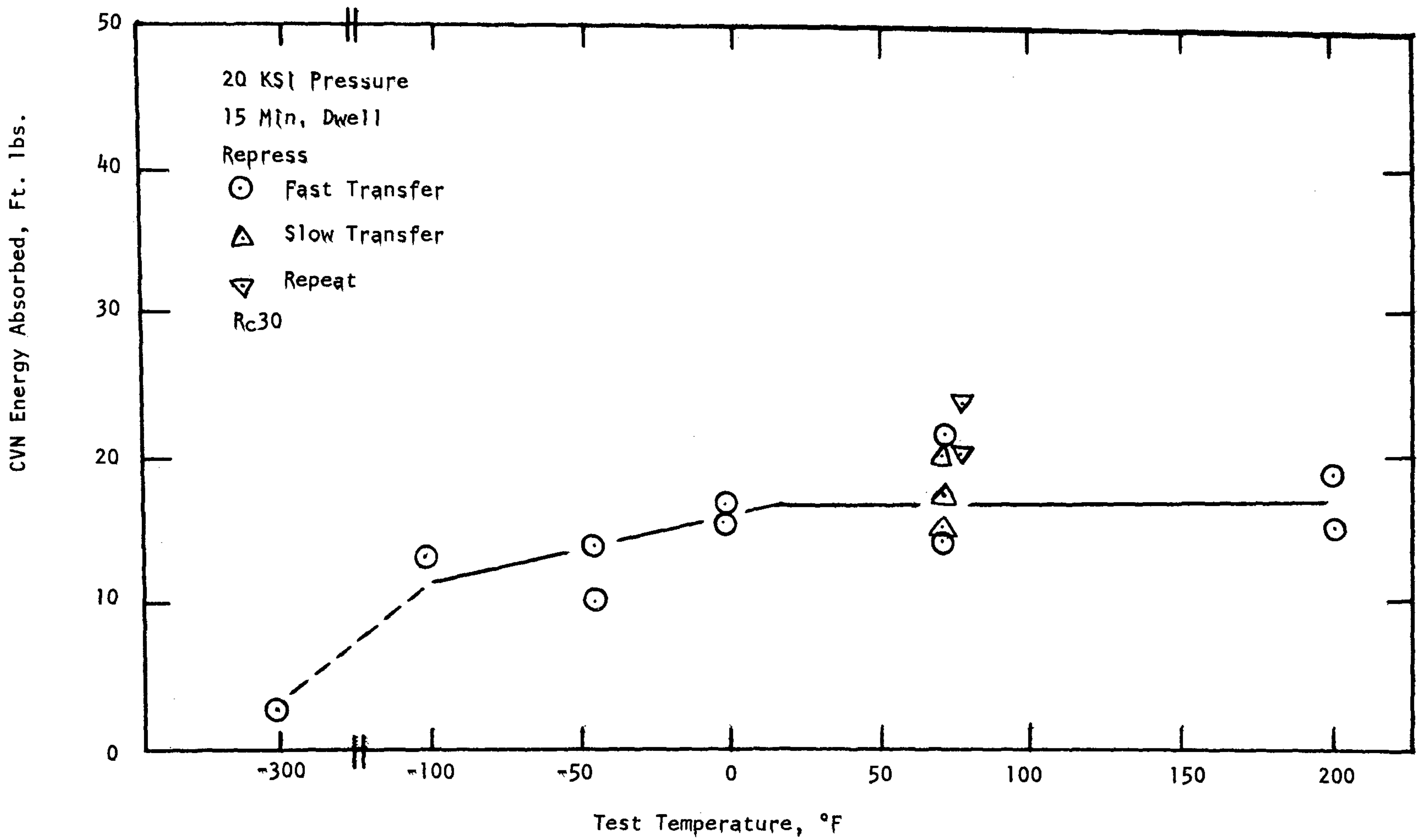


Figure 3-10. Effect of Transfer Time on the Toughness of Isothermally Forged 4620 P/M Test Coupons.

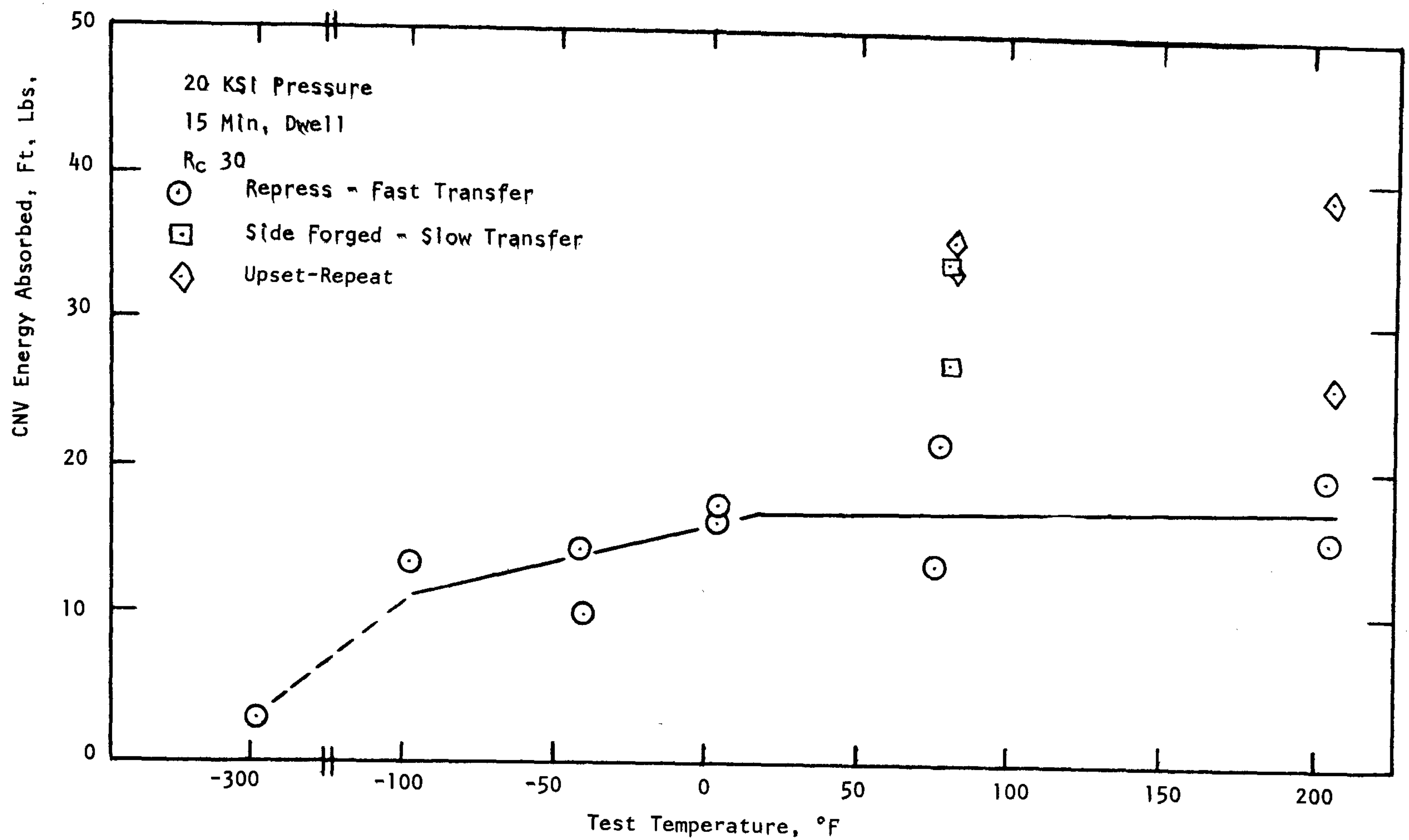
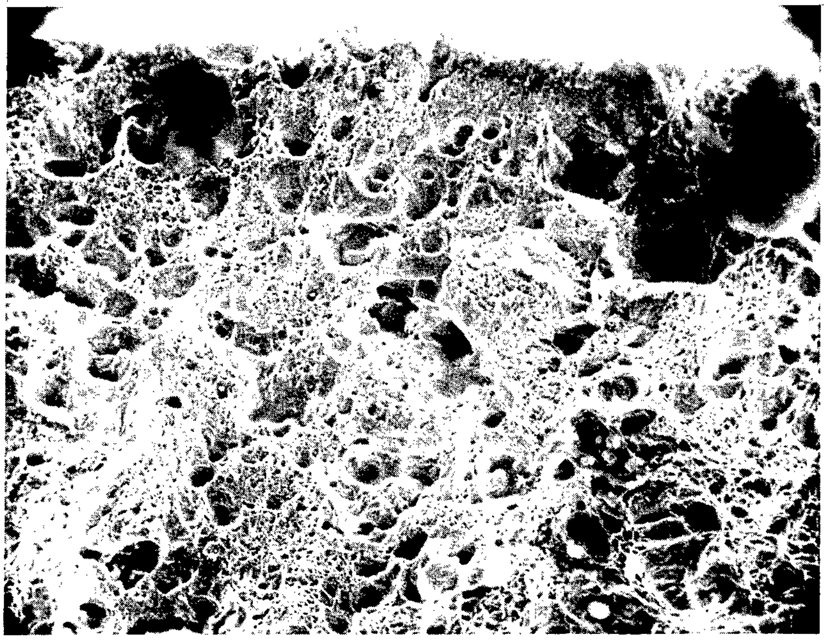
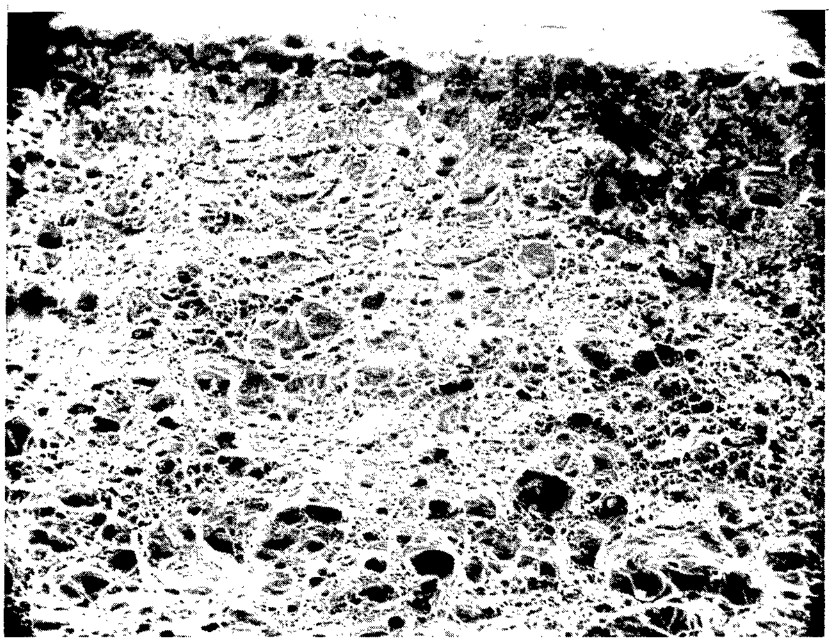


Figure 3-11. Effect of Deformation on Toughness of Isothermally Forged 4620 P/M Test Coupons.



(a) 500X



(b) 500X

Figure 3-12. SEM Micrographs of Ambient Temperature Fractured CVN Samples. (a) 5-Minute Dwell Time - 11 Ft. Lbs. (14.9J); (b) 15-Minute Dwell Time - 20 Ft. Lbs. (27.1J).

3.5 Process Development Summary

This isothermal forging process development program established the following:

- The interrelationship between load, temperature and dwell time is critical for the achievement of full density and complete die fill. For 1650F (900C) preheat temperatures, a forging pressure of at least 10 tsi (138 MPa) must be maintained for at least 15 minutes.

- LF-22 proved to be an excellent oxygen barrier coating as transfer time between the preheat furnace and die set was not critical to property levels. This coating did not build up in the die cavity and was adherent during preform handling. However, ejection remained difficult, as it was for all of the coatings tried.

- Acceptable tensile and impact properties were attainable provided porosity and impurity levels were minimized. Ductility and toughness are enhanced by the presence of metal flow during forging. However, at this low pressure and these poor lubrication conditions metal flow must be minimized to guarantee complete die fill.

4.0 PROCESS DEMONSTRATION

The isothermal forging process was demonstrated on the final drive pinion gear. This gear is a straight spur with 13 teeth. The engineering drawing of the part is shown as Figure 4-1.

In order to demonstrate this process, it was necessary to select a near-net forged shape,design a preform for this shape, design the compaction and isothermal forging tooling to produce the pieces and then initiate forging trials. The following sections expand on these points.

4.1 Design of the P/M Forging

Because the economic justification of P/M lies in material utilization and reduced machining costs, a net or near-net forged shape must be produced. The diameter of this part was large enough and there were enough unknowns about the isothermal forging process, especially in the area of surface finish, that a near-net forging was selected. Grinding or shaving stock of 0.005 in. (13×10^{-4} m) per tooth face remained on the gear teeth. Other machining would be necessary on the bearing surfaces, the reduced diameter section of the shaft and the splined-end of the shaft. The P/M forging is shown in Figure 4-2 and the relationship between the forging and part is shown in Figure 4-3. The cross sectional gear dimensions of the forging and the part are given in Table 4-1.

The extreme aspect ratio of the part presents problems both in compaction of the preform and in forging. Based upon the success of the composite preform approach utilized for differential side gears(2), this forging was designed to be a composite preform forging. As indicated in Figure 4-3, the shaft is forged 4620 bar stock and the gear section is 4620 P/M. During forging, the stepped shaft and the P/M sintered sleeve are deformed to give die fill, densification and bonding across the P/M-bar stock interface.

4.2 Preform Design

A minimum deformation type of preform is necessary for this part. Previous work(3) and the process development have shown that for isothermal forging of 4600 steel powder complete die fill is possible only by limiting the metal movement during forging. Extensive metal flow can not be accommodated for the temperature, time, pressure, friction and grain size applicable to a manufacturing process. As established in Section 4.1, the high aspect ratio of the part makes the composite preform approach attractive, with a shaft being bar stock and a P/M sleeve being positioned on the shaft. Utilizing both the minimum deformation and the composite preform guidelines,a pinion gear preform was designed.

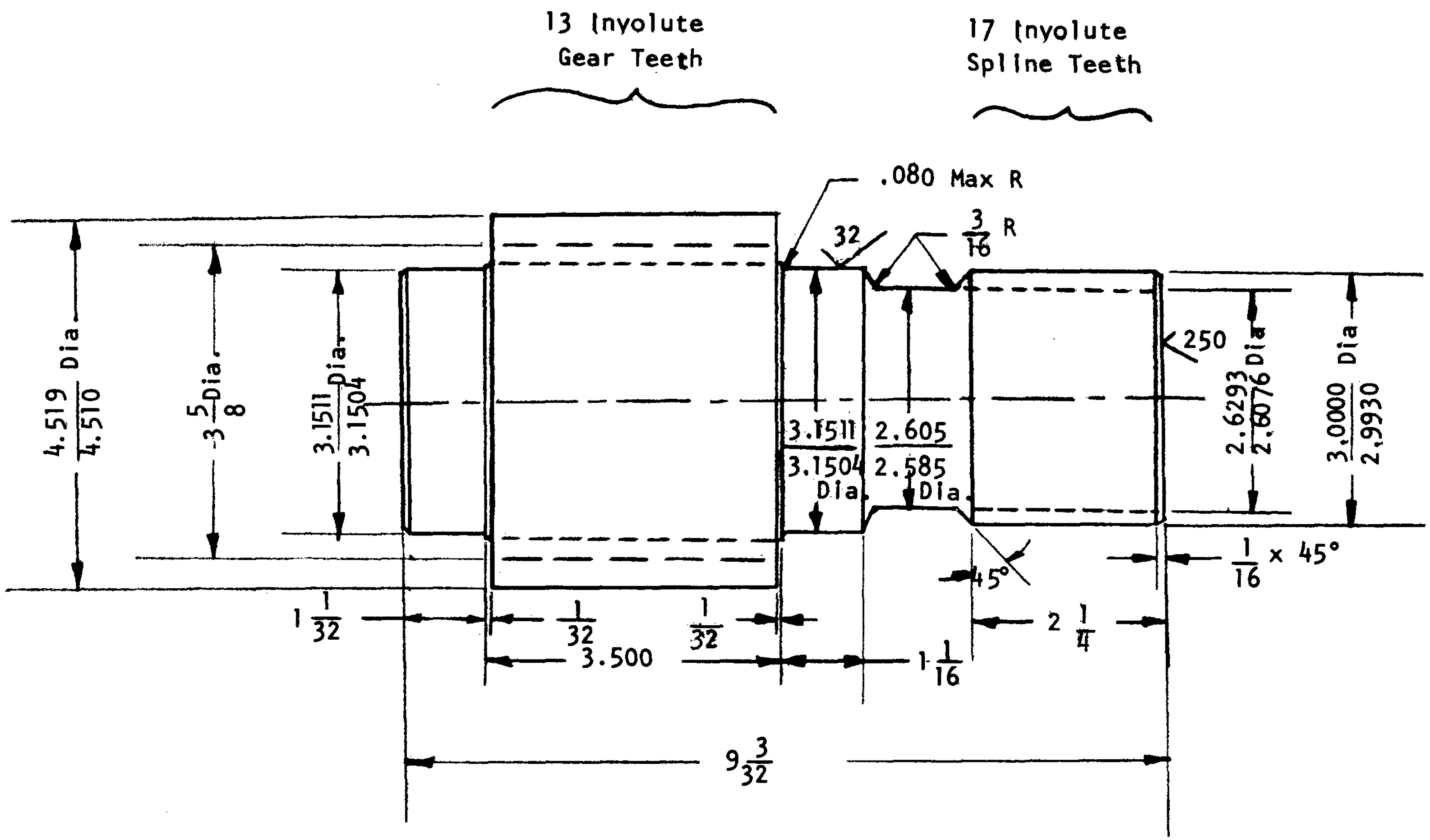


Figure 4-1. Final Drive Pinion Gear for M60 Tank.

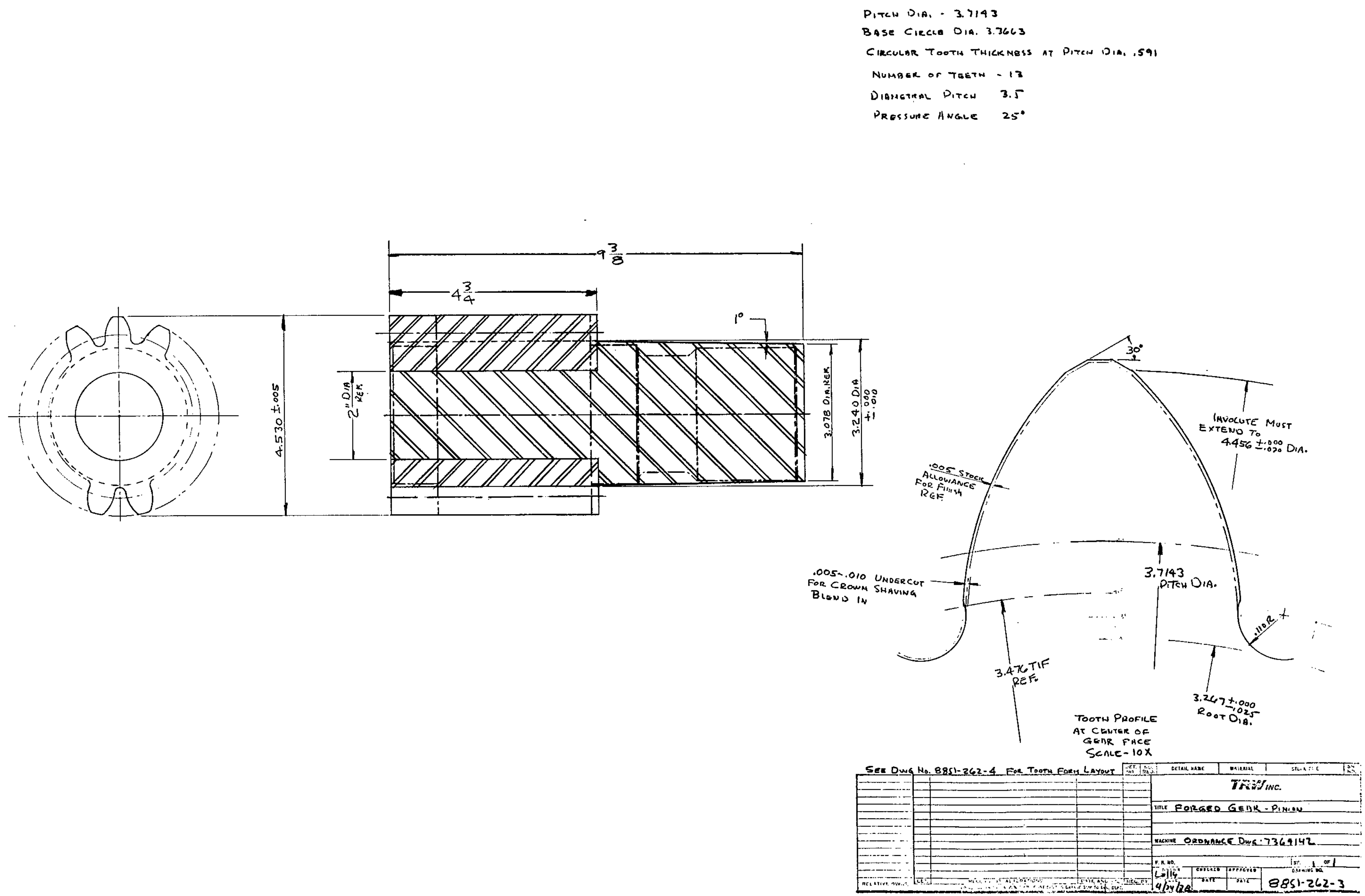


Figure 4-2. Isothermal P/M Forged Gear.

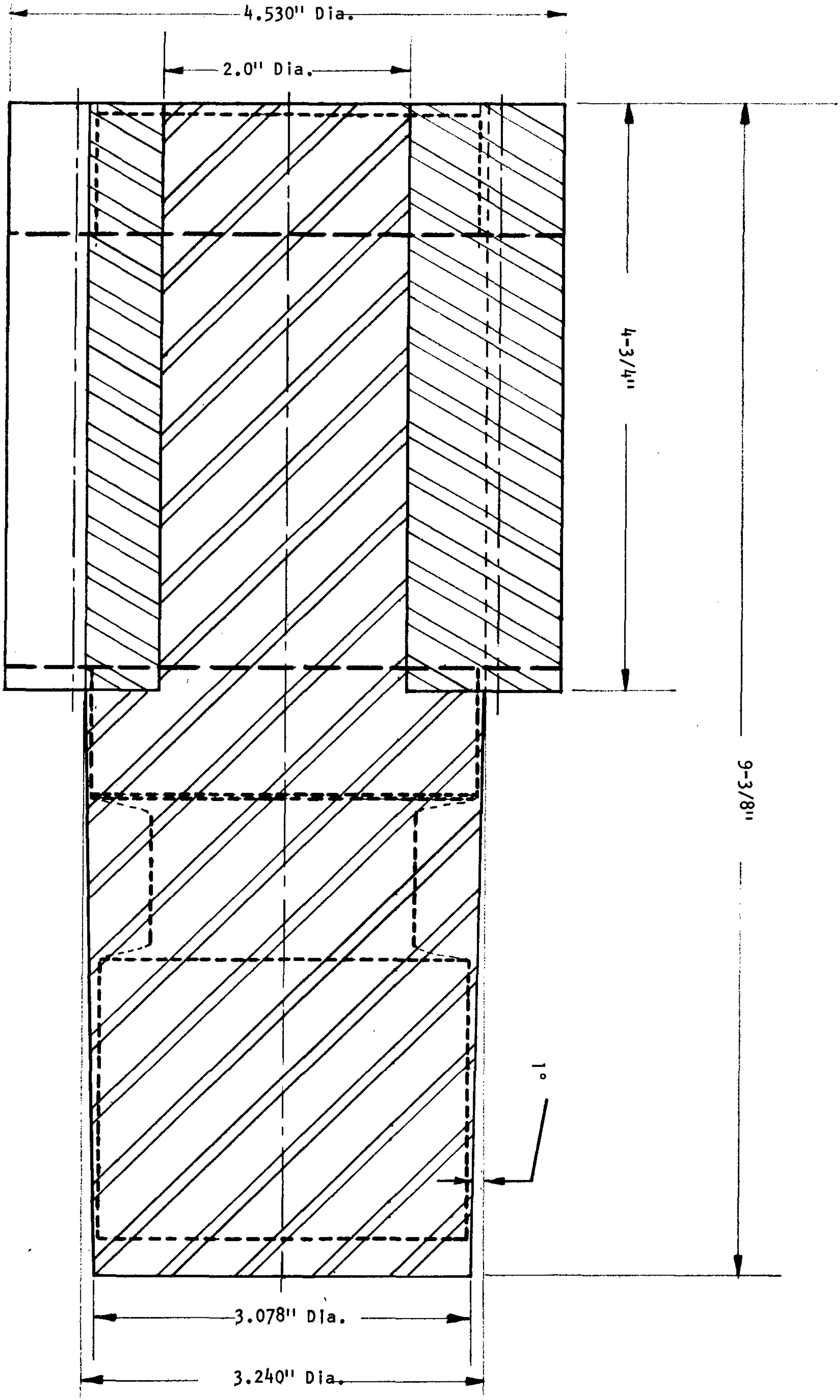


Figure 4-3. Relationship Between the Forged Shape and Machined Shape Of the Final Drive Pinion Gear.

TABLE 4-1

Dimensions of the Gear Sections
Of the Forging and the Finished Part

	P/M Forging	Finished Part
Pitch Diameter - Inches	3.7143	3.7143
Base Circle Diameter - Inches	3.3663	3.3663
Circular Tooth Thickness at Pitch Diameter - Inches	0.591	0.5812
Root Diameter - Inches	3.267	3.267
Involute Extends to - Inches	4.456	4.452/4.472
Tooth Tip Diameter - Inches	4.530	4.510/4.519
Number of Teeth	13	13
Pressure Angle	25°	25°

The high aspect ratio of the P/M sleeve, which would become the gear tooth section, and a need for a uniform preform density require that either a segmented P/M preform or an isostatically pressed preform be used. The segmented preform would consist of several P/M compacts with a gear-shaped cross section in a stackup on a bar stock shaft to form the preform. The sections would be pressed in hard dies and thus have very accurate dimensions and high quality surfaces. The disadvantage of this approach is the high potential for contamination at the interfaces. Because a critical interface already exists between the bar stock shaft and the P/M preform section, at this time it was felt that this preform design was a higher risk than a single P/M section-bar stock shaft preform.

A single section P/M sleeve of uniform density could be compacted by cold isostatic pressing (CIP). This method utilizes flexible tooling which is pressurized by a fluid medium to cause powder compaction. The drawbacks to this process are the lack of precise dimensional control, the end effect (dog bone shape) and the poor surface quality of the pressing. Advantages of CIP are the low tooling cost and the ability to achieve uniform preform density regardless of aspect ratio.

With the above considerations taken into account, the preform depicted in Figure 4-4 was selected. The gear section is compacted powder of 80% theoretical density. Rack teeth are formed on the gear section to minimize metal flow during forging. A stepped shaft is machined from 4620 bar stock.

4.3 Compaction Tooling Design

4.3.1 CIP Tooling Background

CIP tooling was designed to produce the P/M gear section. The first step was to develop the relationship between isostatic pressure and preform density so that tooling dimensions could be determined. Rubber bag tooling with 2.0" (0.05 m) I.D. and 6.0" (0.15 m) length was loaded with 4600 powder tapped to a density of 4.2 gr/cc. Since the actual preform tooling would involve a pressing mandrel, several of these cylindrical compacts contained 0.5 in. (0.013 m) diameter by 4.0 in. (0.10 m) long steel mandrels. Compacts were pressed at pressures from 30 ksi (207 MPa) to 90 ksi (621 MPa). Samples from these pieces were machined, weighed and measured for density determination. The result is the curve shown in Figure 4-5, which shows that a pressure of at least 50 ksi (345 MPa) is needed to achieve 80% of theoretical density.

The compaction tooling dimensions are determined by working backward from the final compact desired dimensions. Given a final compact density (80% in this case) and the initial loose powder packing density (tap density in this case), the dimensional changes during CIP can be determined. Assumptions must include reproducibility of the tap density and uniform radial compaction (no end effect). These assumptions reduce the dimensional change to an area change where the ratio of the initial bag diameter (di) and the final compacted diameter (d_f) equals the square root of the ratio of the final preform density (ρ_f) and the initial density (ρi). That is:

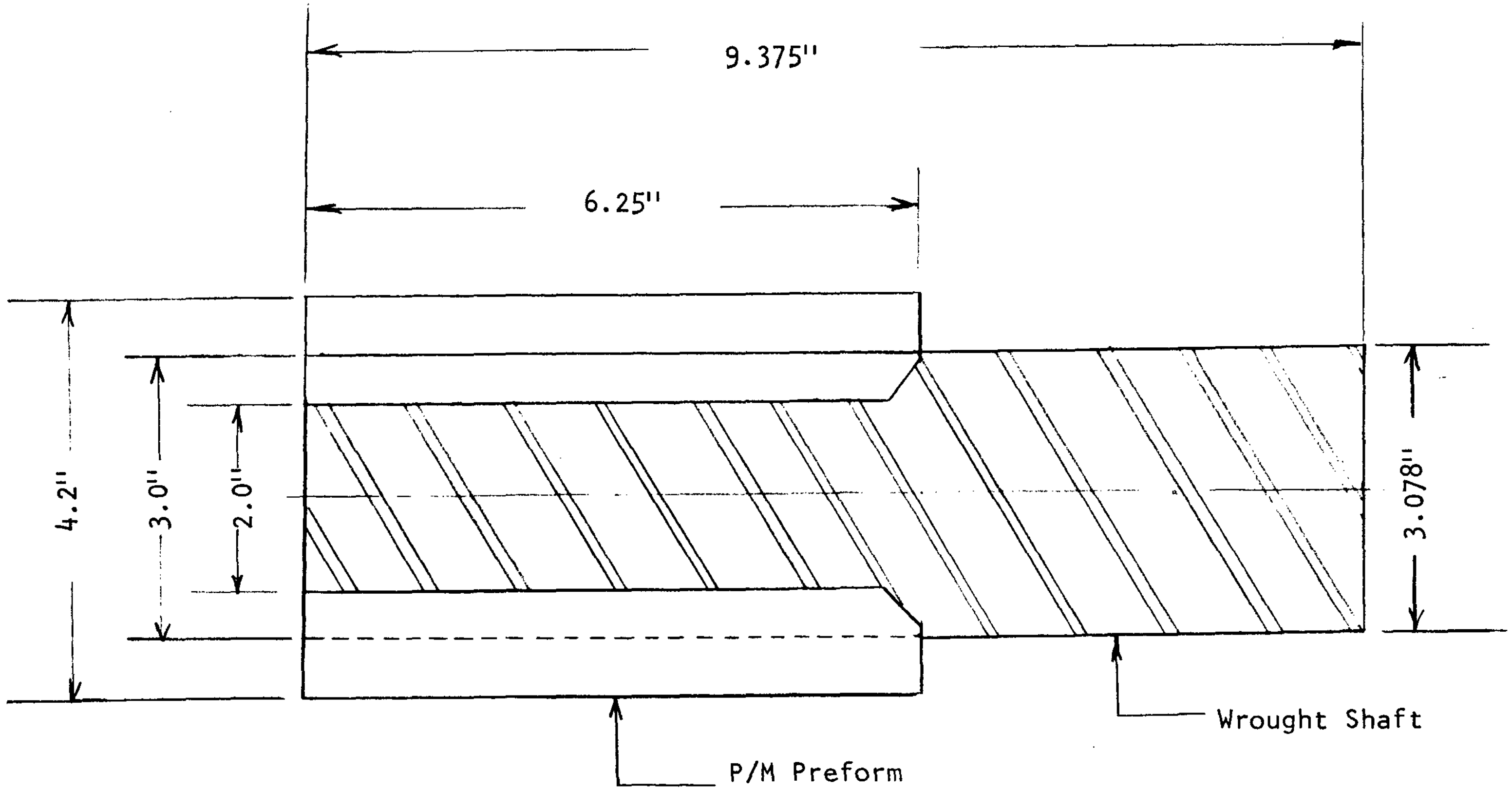


Figure 4-4. Cross Section of the Pinion Gear Preform.

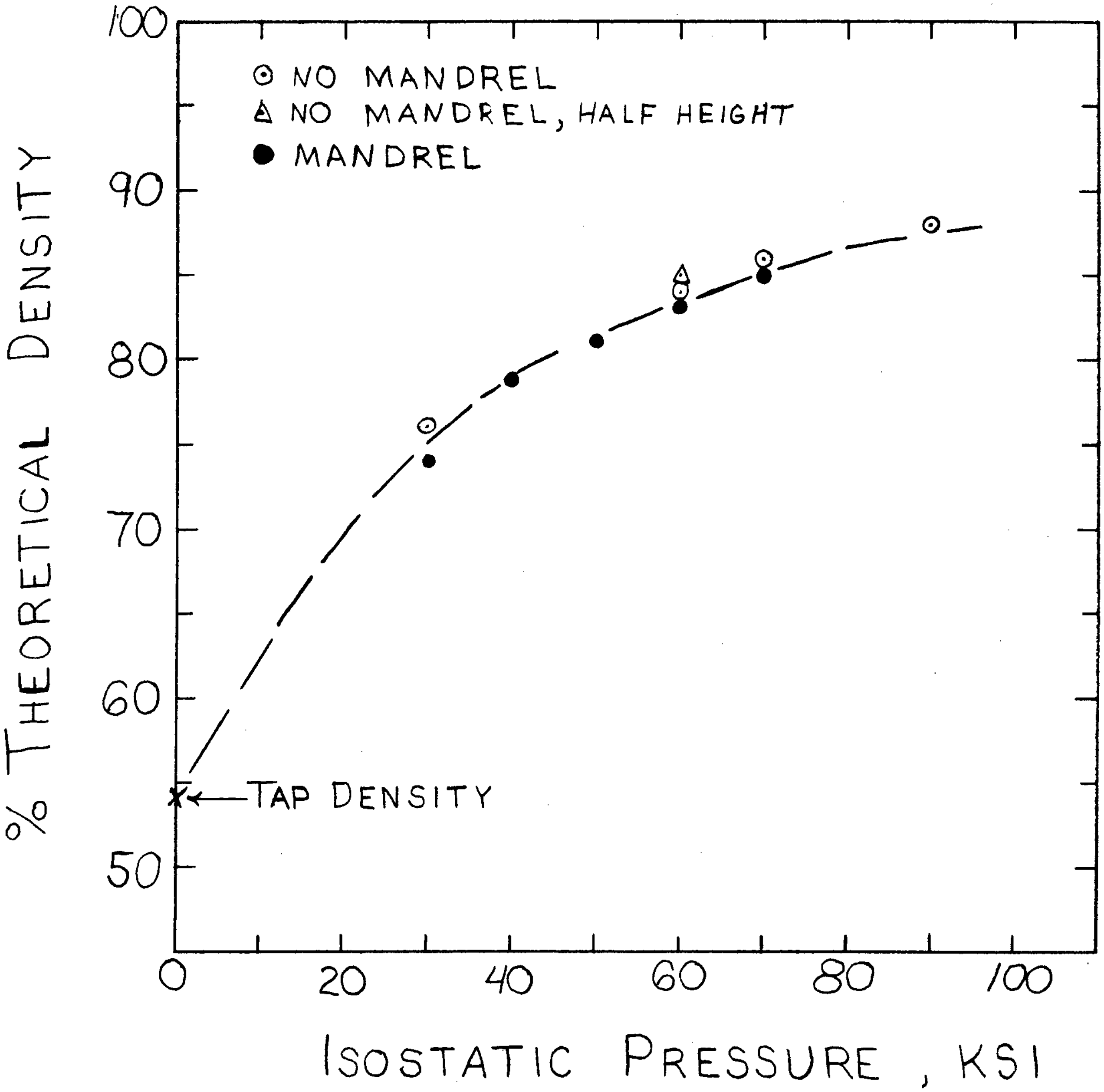


Figure 4-5. Compressibility of 4600 Steel Powder for Cold Isostatic Pressing. Rubber Bag Molds Were 2 In. (0.05m) in Diameter and the Fill Height Was 6 In. (0.15m). Where Indicated, Mandrels Had a Length of 4 In. (0.10m) and Diameter of 0.5 In. (1.3×10^{-2}).

$$d_i/d_f = \sqrt{\rho_f/\rho_i} \qquad \text{eq. (1)}$$

By pressing the preform longer than necessary, ends can be machined off to reduce the end effect problem. Such assumptions are necessary since quantitative relationships between shrinkage, location, piece geometry, tool geometry and pressure have not been developed.

4.3.2 CIP Tooling

The CIP tooling is shown in Figure 4-6. The rubber bag is 0.125 in. (3×10^{-3}m) thick latex. A solid teflon-coated aluminum mandrel is used to hold the I.D. of the powder preform at 2.000 in. (5.1×10^{-2}m). No draft is present on the mandrel. The gear tooth shape is defined by the formed rubber bag which is supported by a formed aluminum cage. The formed bag cross sectional dimensions are given in Figure 4-7. These are the aim internal dimensions of a filled bag. The initial density used in equation (1) is the tap density which was determined to be 4.2 gr/cc. The final density used in equation (1) is 6.4 gr/cc.

4.3.3 Compaction Trials

Compaction trials were run using the CIP tooling to produce preforms. Powder was blended and then weighed into compact weight charges. The molds were filled while they were vibrated to accommodate loose powder densification to the tap density level. A hard felt pad of 0.25 in. (6.4×10^{-3}m) thickness was placed on top of the powder prior to tooling closure to minimize bag wear at the open end of the tooling. The molds were not de-aired prior to CIP. The preforms were compacted at 60,000 psi (414 MPa). A dwell time of at least 30 seconds was used, with rapid de-pressurization following. The bags were then stripped from the compacts, dried if necessary and re-used.

After the first run, an immediate problem surfaced. The rubber bag and steel powder stuck together, making stripping very difficult. The sticking mechanism was rubber intrusion into the powder during compaction. The use of RTV 60* as a bag lining eliminated the sticking problem, although the RTV 60 was subject to wear during compaction. A solid RTV 60 bag was made and also performed successfully. In the future, no latex rubber should be used with steel powders. Urethane tooling should be employed specifically to minimize stripping problems and to maximize mold service life. Other candidate materials are polyvinyl chloride and polyethylene.

The compact shape showed that compaction was not totally in the radial direction. The result was the usual dog bone shape which is shown schematically in Figure 4-8. Typical dimensions are given in Table 4-2 for a pressed preform. The middle section of the preform essentially experienced radial compaction. The end experienced both radial and axial compaction, with the mandrel restricting axial compaction in the center region of the preform end. The result is a variation in radial and circumferential dimensions as a function of position. Effort to develop the necessary relationships to predict CIP shapes was beyond the scope of this program.

* RTV 60 is a silicone rubber curable at room temperature to a durometer of 60 (Shure A).

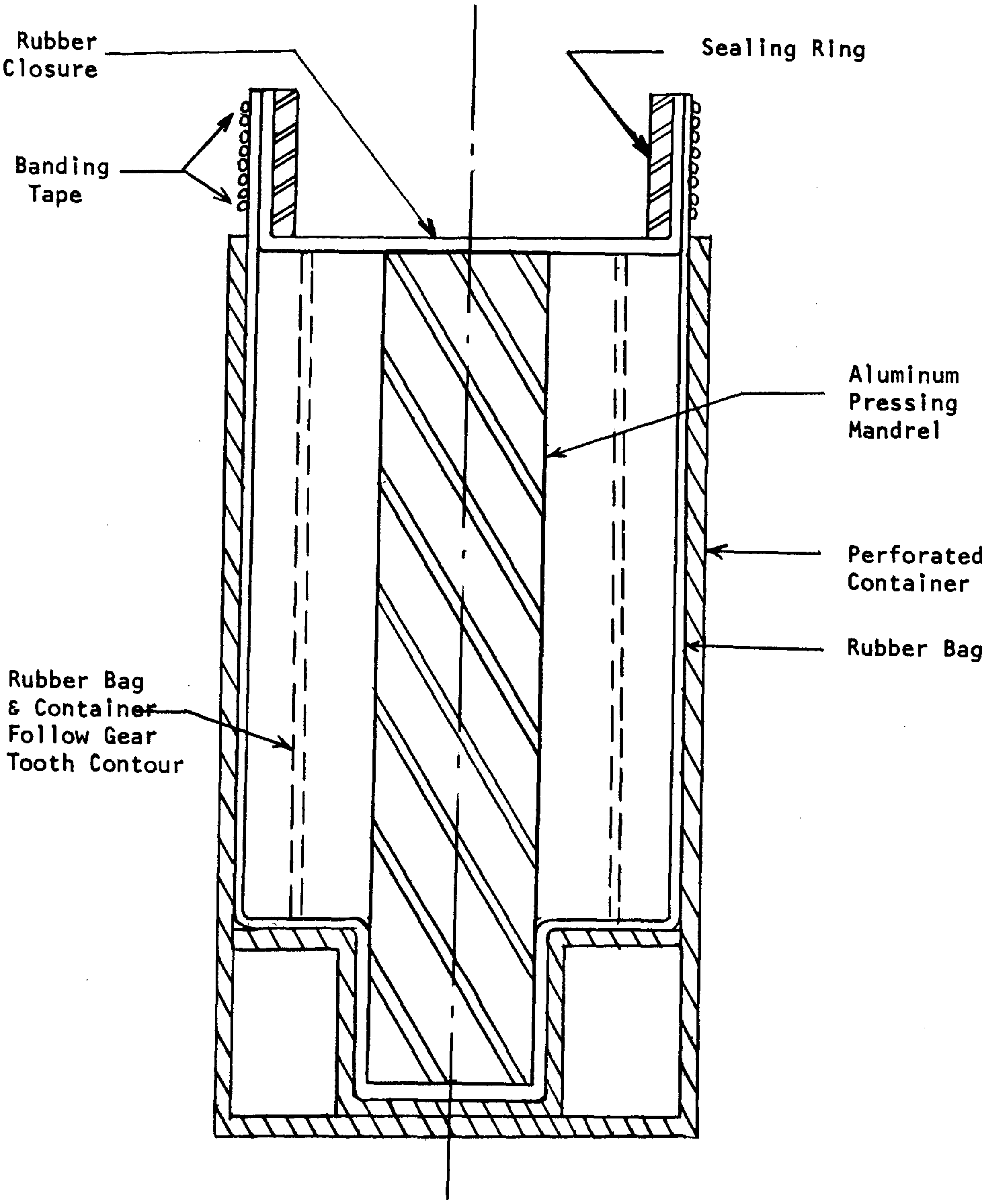


Figure 4-6. Schematic of Cold Isostatically Pressed Preform Tooling.

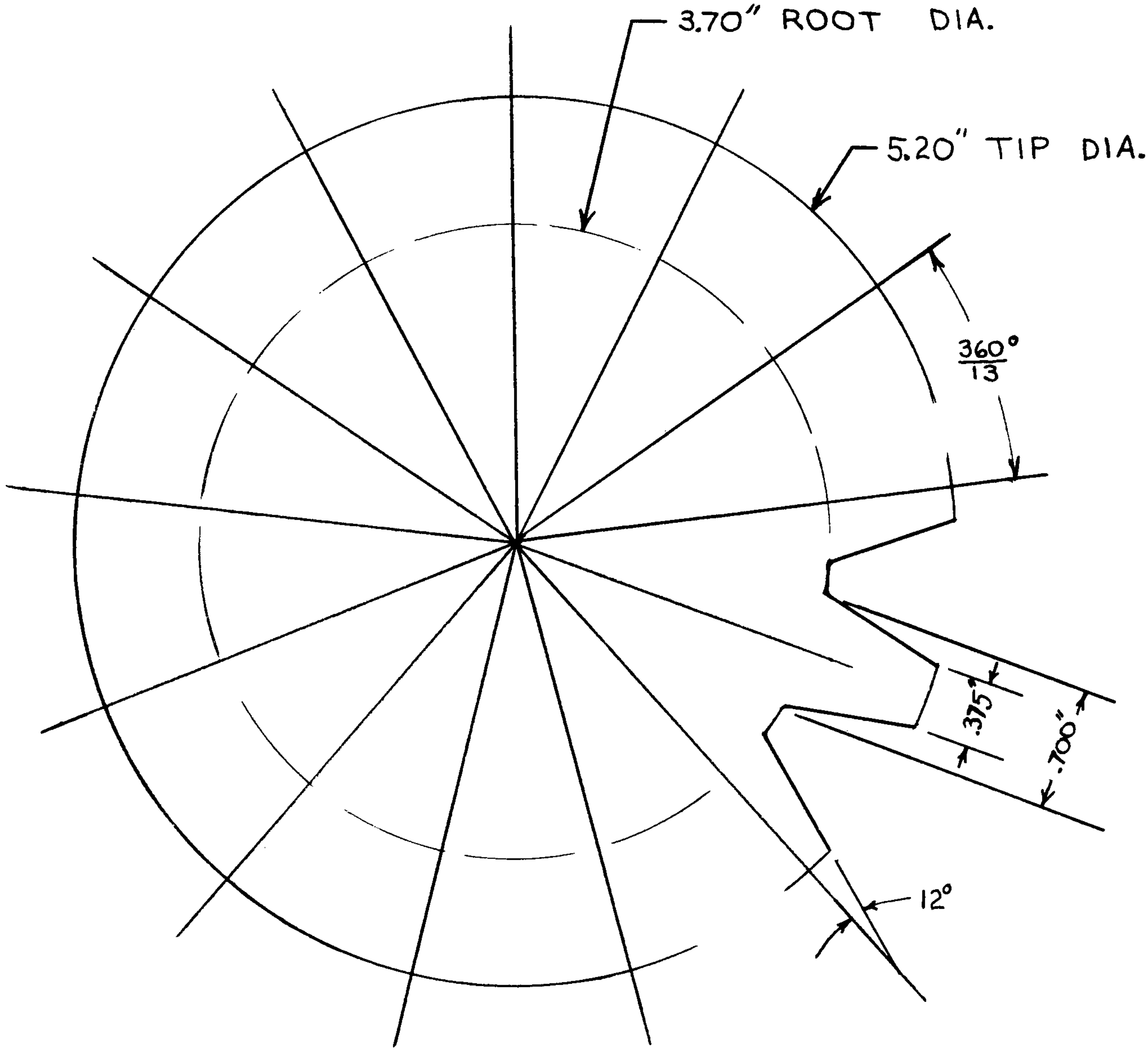


Figure 4-7. Cross Section of Preform Cavity in Rubber Bag Mold for CIP

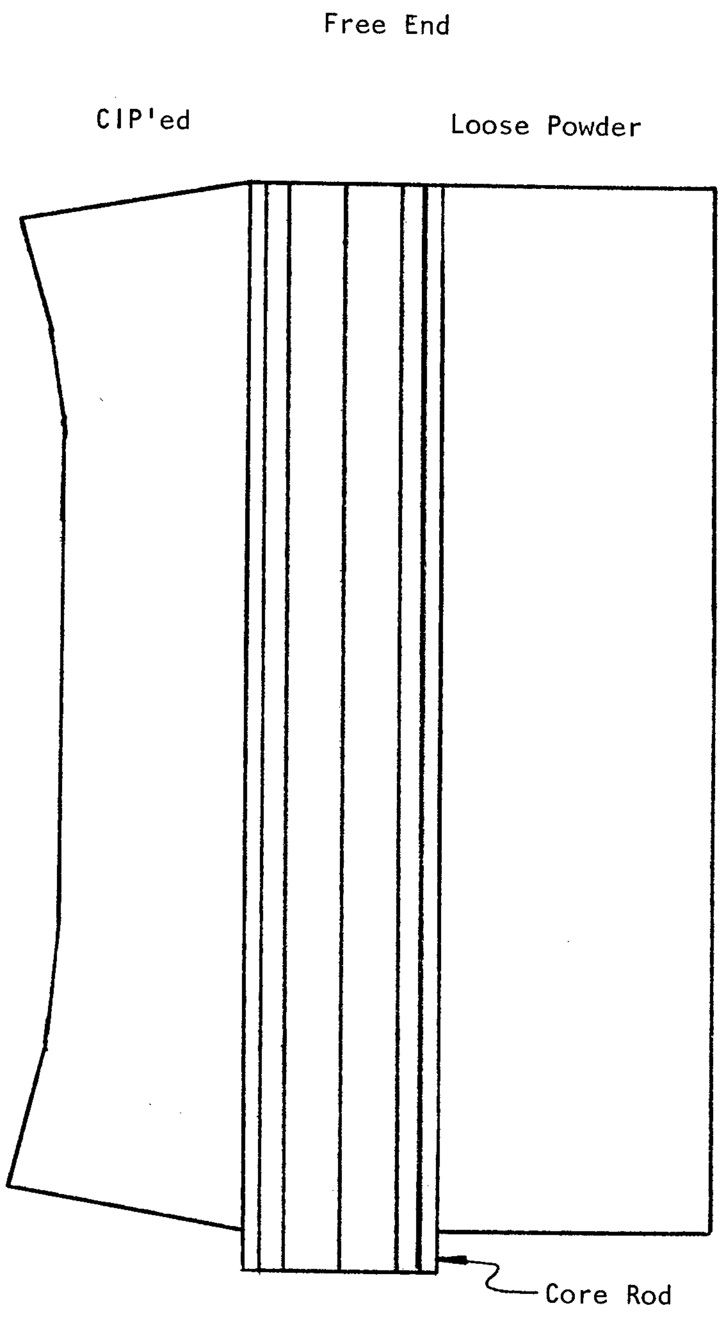


Figure 4-8. Schematic of CIP'ed Preform Illustrating the Compacted Shape Change during CIP.

TABLE 4-2

Dimensions of CIP Preform* (60 ksi Pressure (414 MPa))

Position (Inches from Bottom	Tooth Tip Diameter (in)	Root Thickness (in)	Tooth Height (in)
Top	4.62	0.64	0.70
7	4.59	0.64	0.69
6-1/2	4.57	0.63	0.66
6	4.53	0.63	0.67
5-1/2	4.49	0.62	0.66
5	4.47	0.60	0.67
4-1/2	4.43	0.60	0.64
4	4.10	0.58	0.62
3-1/2	4.45	0.58	0.61
3	4.46	0.59	0.61
2-1/2	4.48	0.61	0.61
2	4.49	0.60	0.61
1-1/2	4.52	0.63	0.62
1	4.55	0.63	0.63
1/2	4.60	0.63	0.63
Bottom	4.67	0.63	0.63

* 1 in. = 2.54×10^{-2}m.

4.4 Isothermal Forging Tooling Design

Isothermal forging tooling was designed and built to accomodate features used for conventional P/M forging tooling and die materials and heating components used for isothermal forging. A nickel-base superalloy, IN 100, is the best commercially available material for isothermal forging tooling, and was chosen as the die and punch material for this program. Because IN 100 is expensive and contains strategic elements (Co), a reinforcing ring was designed so that the amount of IN 100 could be minimized. The following sections detail the die design, manufacturing procedures and assembly.

4.4.1. Tooling Design

Isothermal tooling was designed to produce a forging free of a parting flash line and low or no draft angles. A schematic of this tooling is shown in Figure 4-9. The tooling consists of a ring die, shaped top punch and cylindrical bottom punch, all made from IN 100. A wire wound ring which supports the die set is described in Section 4.4.3. The die can be heated by induction, by cartridge heaters, or both. Also, an atmosphere curtain may be employed if necessary.

The critical dimensions of the die are the cavity dimensions. These dimensions are determined from the final dimensions of the forging. The procedure is as follows:

1) calculate the forging dimensions at the forging temperature (1650F [900C]) using the thermal expansion factor of 4620 steel from ambient to the forging temperature,

2) set the IN 100 die cavity dimensions equal to the forging dimensions at the forging temperature, and

3) calculate the ambient temperature dimensions of the die cavity based on the thermal contraction of IN 100.

In terms of equations, this reduces to:

$$D_{IN\ 100} = \left[\frac{1 + \alpha_{4620}\ (T_f - T_a)}{1 + \alpha_{IN\ 100}\ (T_f - T_a)}\right] D_{4620} \qquad \text{eq. (2)}$$

where $D_{IN\ 100}$ is the ambient temperature (T_a) dimension of the IN 100 die cavity with relation to the ambient temperature dimension of the 4620 steel forging. The forging temperature is T_f and the thermal expansion factors of the 4620 steel, and IN 100 superalloy are α_{4620} and α_{IN100} respectively. The gear cavity cross sectional dimensions are given in Table 4-3 to compare the forging dimensions and the IN 100 dimensions at ambient. The thermal expansions of the 4620 steel and the IN 100 die between ambient and 1650F (900C) were 8.5×10^{-6} in/in/°F (4.72×10^{-6}/m/m/°C) and 8.8×10^{-6} in/in/°F (4.89×10^{-6} m/m/°C). Thus at ambient the gear cavity is slightly smaller than the forging as the dimensions indicate. No draft was allowed in the gear cavity, while a 1° to 1-1/2° taper was designed in the shaft section since it would need to be finish turned.

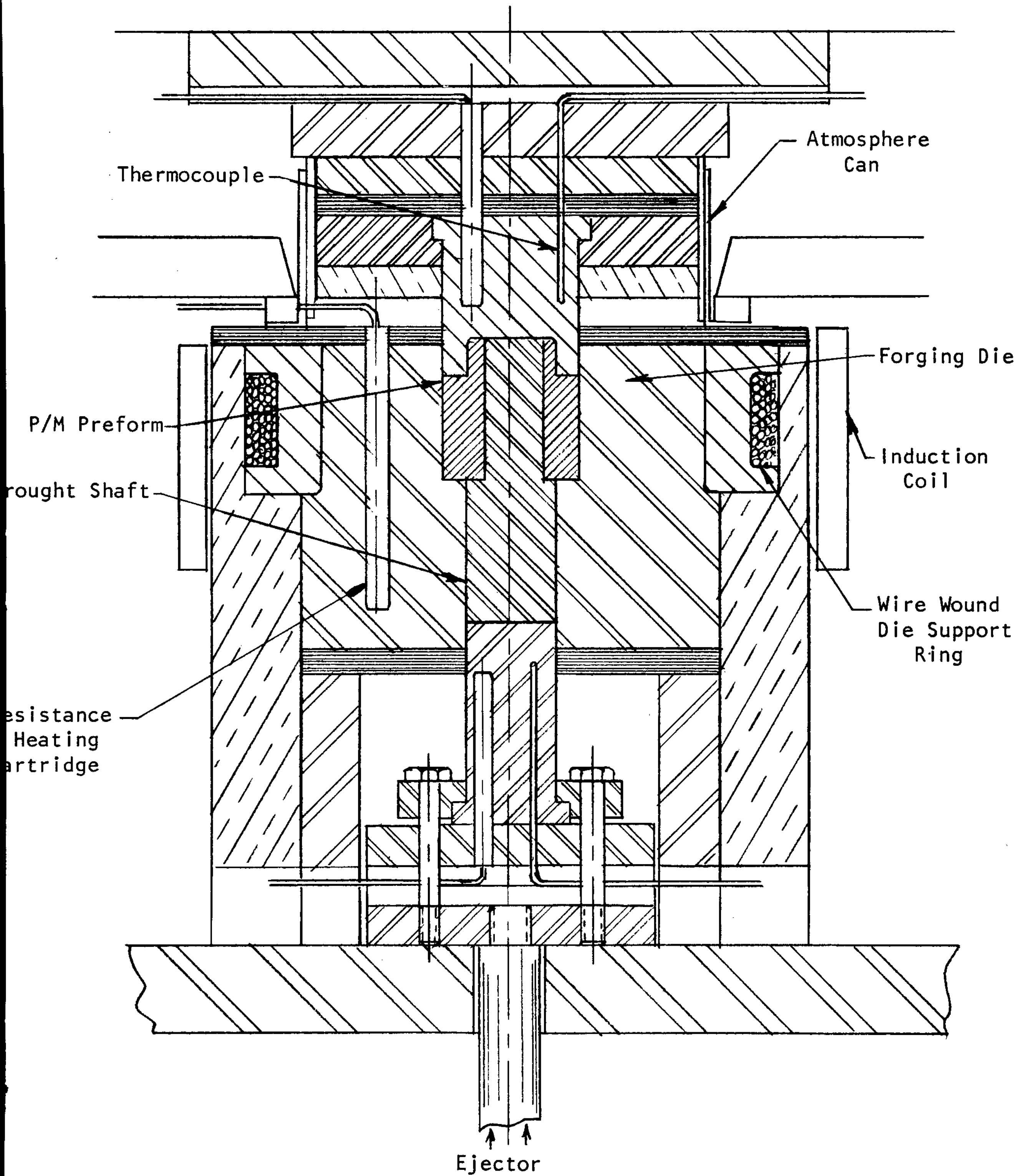


Figure 4-9. Schematic Illustration of the Hot Die Forging Tooling and Die Set.

TABLE 4-3

Room Temperature Gear Dimensions*

	4620 P/M Forging	IN-100 Die Cavity
Pitch Diameter (inches)	3.7143	3.713
Base Circle Diameter (inches)	3.3663	3.365
Circular Tooth Thickness at Pitch Diameter (inches)	0.591	0.591
Number of Teeth	13	13
Pressure Angle	25°	25°
Involute Extends to (inches)	4.456	4.454
Tooth Tip Diameter (inches)	4.530	4.528
Root Diameter (inches)	3.267	3.265

* 1 inch = 2.54×10^{-2} m.

A gear shaped top punch with a flat face was dimensioned to yield a 0.004 inch (1.0×10^{-4}m) clearance gap between the punch and die cavity. A cylindrical bottom punch was designed to fit the bottom shaft diameter with the same clearance. Normal clearances fro P/M forging dies are 0.004 to 0.006 inch (1.0×10^{-4}m) gaps per side.

Cartridge heater holes (4) were spaced equally around the center of the die cavity and ran parallel with it. Later four more heater holes were added on the same diameter.

A wire wound support ring was designed to provide compressive loading around the circumference of the die during isothermal forging. The purpose of this ring was to prevent catastrophic IN 100 die failure due to cast-in porosity and/or carbide clusters. Such failure has been experienced in the past. Because the support ring would be operating at the isothermal forging temperature, a refractory metal with high temperature strength was a necessary selection. Drawn tungsten wire of 0.014 inch (3.8×10^{-4}m) diameter was utilized. Properties of drawn W-wire are given in Table 4-4.

Tungsten and IN 100 have widely different thermal expansion factors (α). Between ambient and 1650F (900C), α_W is 2.56×10^{-6} in/in/°F (1.42×10^{-6} m/m/°C) and $\alpha_{IN\ 100}$ is 8.8×10^{-6} in/in/°F(4.89×10^{-6}m/m/°C). This means that the wire wrapping will expand much less than the inner ring die and thus considerable tensile stresses can build up in the wire as compressive hoop stresses build up in the die block. For this reason, the ambient temperature fit of the support ring on the die block is critical. Using the approach outlined in Appendix I, the following dimensions and conditions were determined:

- A clearance gap of 0.050 inch (1.3×10^{-3}m) should exist at ambient between the stress ring and the die block.

- A wire wound section with an I.D. of 12.5 inches (0.32m), a height of 6.5 inches (0.17m) and a thickness of 0.5 inches (1.3×10^{-2} m) should be fabricated.

- The wire should be wound in close pack array at zero tensions. This amounts to 47 layers of wire with 433 wraps per layer, and a total wire length of 68,800 feet (20,995 m).

- The wire must be protected from oxidation.

TABLE 4-4

Strength of Cold Drawn Tungsten Wire [7]

Drawn Wire Gage		Ambient Tensile Strength	
in.	(m)	psi	(MPa)
0.040	(1×10^{-3})	256,000	(1765)
0.020	(0.5×10^{-3})	284,000	(1958)
0.008	(0.2×10^{-3})	355,000	(2448)
0.004	(0.1×10^{-3})	427,000	(2944)
0.008	(0.2×10^{-3})	582,000	(4013)
Recrystallized Wire		157,000	(1083)

4.4.2 Tooling Fabrication

IN 100 castings were obtained from which the top and bottom punches, the die block and the support ring base were machined. The castings were approximately 1/8 inch (3×10^{-3}m) over dimension on outside diameters and heights. A core hole of 2.0 inches (5.1×10^{-2}m) was cast in the die block.

IN 100 is difficult to machine, with grinding and EDM being the primary methods of machining utilized. Single point turning using Borazon or diamond tooling can be performed. These methods were used to machine the die components.

A critical match-up is that between the top punch and the die gear cavity. A technique was successfully used to achieve very tight dimensional control. The top punch was cut by traveling wire EDM using programmed wire head motions. This means that a precision of 0.0002 inches (5.1×10^{-6} m) is held during cutting. Using a correction factor to allow for the proper clearance gap and electrode burn zone,

conventional EDM electrodes were then wire EDM cut. These were then used to sink the gear shape into the die block. The result was a die cavity/punch match-up with the appropriate clearance gap.

Prior to use, the die cavity was polished using a hard felt plug and an alumina slurry polishing compound. The faces of the punches were also polished.

Tungsten wire was wound onto the IN 100 support ring manually. The first wrap was tack welded in place and thereafter an attempt was made to maintain a close pack array. Because of gage variations, twists and kinks in the wire, it proved impossible to maintain the close pack array. To counteract this difficulty, a single wrap of stainless steel foil was applied approximately every 10 layers. Since wire lengths of 650 to 2000 ft (200 to 600 m) were wrapped, wire ends were fastened with polystyrene and Eastman 910 glue during wrapping. After wire wrapping, a double layer of 310 S.S. sheet was wrapped and welded in place. The wire filled cavity was evacuated, leaving a residual partial pressure of argon.

Since no clearance could be accommodated between the wire and the IN 100 ring, that together make up the shrink ring, calculations indicated that the theoretical interference fit between the wire winding and the IN 100 at 1650F (900C) would create a shrink fit pressure of 34,530 psi (241 MPa). This pressure would create a compressive hopp stress of 79,335 psi (554 MPa) at the inner bore of the die block and a maximum tensile hoop stress of 449,515 psi (3140 MPa) in the W-wire if zero clearance fits were used. The latter stress exceeds the yield and tensile strength of the wire, which must be avoided. However, the imperfection in the winding, the wire shape (line contact instead of planar contact for stress transfer), the presence of foil wraps and some slippage of wire during stressing should reduce the tensile stress in the wire to acceptable levels. Additional factors such as temperature gradients due to the skin effect associated with induction heating can also lower the effective interference between the wire winding and the IN 100 ring. A clearance of 0.005 inch (1.3×10^{-4} m) was provided between the support ring I.D. and the O.D. of the die block.

Upon assembly of the die set, thermocouples were tack welded to the die block around the top of the gear cavity, to the support ring skin, and to the base of the die block for purposes of temperature measurement. The bottom punch was welded to an RA333 alloy ejector rod. The top punch was to be used as a floating punch.

4.5 Spur Pinion Gear Forging - First Iteration

4.5.1 Preform Sintering

P/M compacts of the gear section and bar stock shafts were assembled and then sintered at 2200F (1204C) for one hour in an atmosphere of H_2 + 1 to 2 v/o CH_4 gas mixture. The inlet dewpoint of the gas was -40F (-40C). Sintering bonded the shaft and P/M section to allow handling without fear of separation.

After sintering, milling of the gear section was necessary to provide enough clearance to fit into the die. This milling would not be necessary for production since adjustments in CIP tooling dimensions could now be made to yield the appropriate preform shape.

4.5.2 Preform Coating

Based on the success of the LF-22 coating for the test coupon forging trials in terms of oxidation protection, adherence in the furnace and during handling, and for die release, a warmed preform was painted with LF-22. After the coating had dried, the piece was ready for preheating.

The top punch was also coated with LF-22 by the same procedure.

4.5.3 Preheating Practice

The die set was heated to 1650F (900C) using both induction and the four cartridge heaters. The cartridge heaters were used to carry the bulk of the heating load and were very slow. Since this was the first heat-up of the die block, a slow heating rate was desirable.

The coated preform and top punch were charged into a muffle furnace heated to 1650F (900C) under a protective atmosphere of H_2 gas. Heating time was 20 minutes after temperature stabilization.

4.5.4 Isothermal Forging Trial

The goals of this first forging trial included:

1) the development of a forging procedure that was rapid yet safe;

2) break-in of the die block and punches; and

3) pinpointing problem areas such as ejection, transfer, etc.

The forging was performed on a 150-ton (1.3 MN) hydraulic press with a ram approach speed of 354 inches per minute (0.15 m/s), a loading speed of 94 inches per minute (0.04 m/s) and a withdrawal speed of 470 inches per minute (0.20 m/s)

Since this was the first run, a lower-than-normal load of 105 tons ($\sim$7 tsi (95 MPa)) was used so that the loading-forging-ejection procedure could be checked. The press was initially set at 25 tons (0.2 MN) load, the lowest possible for this 150-ton hydraulic press, and increased to 105 tons (0.9 MN) after the preform and top punch were inserted into the die.

Transfer and insertion of the preform into the die was slow, taking roughly four (4) minutes. The slowness was due partly to procedure problems but mainly due to insertion difficulty as the daylight between the ram and the top of the die was approximately equal to the preform height. Once the top punch was inserted, the ram was activated and the load was taken up to 105 tons (0.9 MN). A dwell time of 20 minutes was needed, with the last 15 minutes being time at the desired 1650F (900C) temperature.

An ejection problem was encountered. Initial efforts to eject the forged piece were unsuccessful. Ejection was achieved the next day by dropping the die temperature to 1200F (650C) and then rapidly heating the die by induction to 1650F (900C). This rapid expansion of the die relieved the internal stresses sufficiently to allow ejection. Once the forging moved in the die ejection proceeded smoothly. The forging flashed non-uniformly around the top punch which acted to lock the punch and forging in the die.

Inspection of the forging showed that the top inch (2.5×10^{-2} m) had been deformed to the involute gear shape to completely fill the die cavity and that die fill for the remaining gear section length was incomplete. Generally, teeth tips were filled but the faces were not. Also, the bar stock shaft deformed in the gear section, but the shaft section was not deformed.

During attempts to eject the part, many of the thermocouples were removed from the die block. To replace these the die block was cooled to room temperature at which time it was inspected. Inspection revealed that the stainless steel cover skin on the wire wound support ring had ruptured. This most likely occurred during the snap heatup of the die block during ejection. The stainless steel skin of the ring overheated during the intense induction heating period. The cover skin was cut off of the support ring and several layers of damaged wire were removed. A new skin was welded in place and the assembly was evacuated. Because of this problem and the slow heating response with four cartridge heaters, four more cartridge heater holes were EDM'ed into the die block prior to reassembly.

Metallographic examination of the forging showed metallurgical bonding across the shaft preform interface, residual porosity in the P/M section (this was expected due to low load), some lubricant entrapment at the gear surface and an interface gap between the P/M and shaft sections at the free end of the gear section. The shaft P/M interface is shown in Figure 4-10. Bonding is evident as no definite boundary line exists between the materials. At the free end of the forging, a gap exists between the P/M and bar shaft as shown in Figure 4-11. Incomplete seating of the P/M section on the shaft was evident at the constrained end of the gear section. It remains to be seen if these gaps would exist at full die fill and higher forging pressures. Also shown in Figure 4-11 is lubricant entrapment at the surface of the P/M section. Residual porosity is shown in Figure 4-12. Comparison of parts (a) and (b) show that, in general, the large pores have been closed in the top section of the gear where complete die fill was experienced, but that large pores still remain in sections where incomplete die fill occurred. This result is expected.

4.5.5 Conclusions from the First Trial

The results of the first trial indicate both problems and promise. First, ejection is a major problem. However, the piece did break loose from the die walls and was ejected. The use of a parting agent appears to be necessary.

Bar Stock | P/M

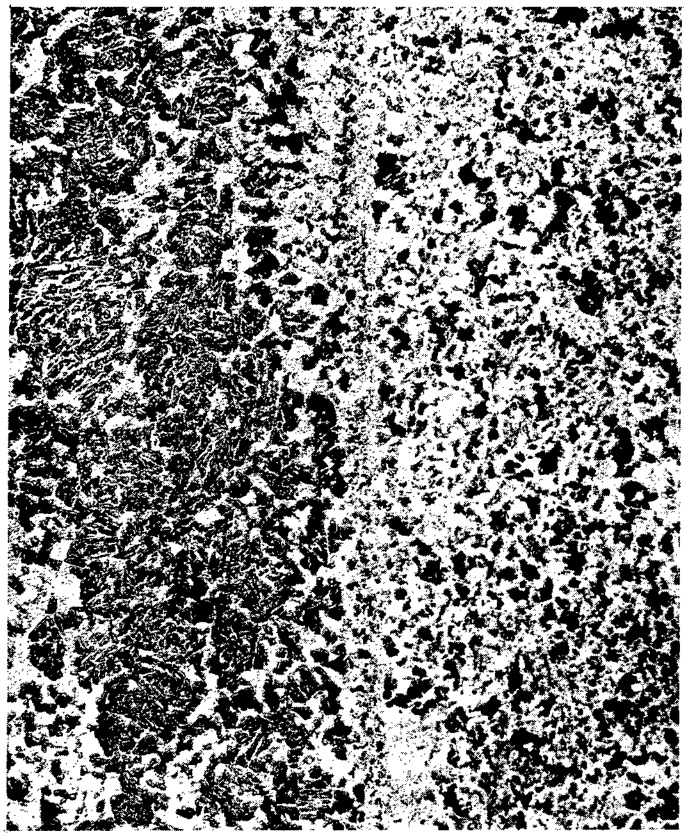


Figure 4-10. Polished and Etched (2% Nital) Cross Section Showing the Bar Stock/P/M Interface at a Location ~0.5 inch (1.3 cm) from the Free End of the Forging.

100X

Figure 4-11. Free End of the Forging Showing a Gap in the Bar Stock/ P/M Interface.

100X

(a) 100X

(b) 100X

Figure 4-12. Residual Porosity in the Gear Forging (a) Polished Section from the Forging Top Where Complete Die Fill Was Achieved; (b) Section from the Constrained End of the Gear Section Where Die Fill Was Incomplete.

Second, the dimensions of the top of the forging where die fill was complete were very good. Measurements taken across pins fell within the desired dimensional range. Also, the surface finish was not usable as forged but was uniform and would clean up by face grinding or shaving to an acceptable part.

Third, the shaft in the gear section had upset; this aids both bonding across the interface and densification in the P/M section. The P/M preform had not been completely seated on the shaft due to the low forging pressure. A gap in the interface was present at the top of the forging.

Fourth, lubricant entrapment in the initially porous P/M surface is evident. If the entrapment can be maintained to depths of ≤ 0.005 inch (1.3×10^{-4}m), this is no problem. In this forging, depths from negligible to 0.010 inch (2.5×10^{-4} m) were found.

Fifth, the heating response of the die block showed that induction was fast but the stainless steel cover skin would overheat and that four cartridge heaters were too slow. Provisions were made to add four more cartridge heaters to the die block.

4.6 Spur Pinion Gear Forging - Second Iteration

4.6.1 Preform Sintering

Preforms were sintered using the same conditions as described in Section 4.5.1. A temperature of 2200F (1204C) for 1 hour in an H_2+1 to 2v/o CH_4 gas atmosphere yields clean, low oxygen preforms.

4.6.2 Preform Coating

A coating of LF-22 was applied to a sintered preform following the procedure established for the first forging trial (section 4.5.2). A parting agent of boron nitride was brushed over the LF-22 coating. Boron nitride is a well established parting agent for easing die release.

4.6.3 Preheat Practices

The coated preform and top punch were heated to 1750F (954C) in hydrogen prior to forging. This higher temperature was chosen to offset the temperature drop during transfer to the die.

The die block was heated by the eight cartridge heaters to approximately 1680F (916C). The die temperature was not perfectly uniform and ranged from 1650F to 1690F (900 to 921C) around the top of the gear cavity.

4.6.4 Forging Trial

Once the preheating of the die and preform was complete, isothermal forging was initiated on a 150-ton (1.3 MN) hydraulic press. The preform was loaded into the die cavity, the top punch was inserted and the full load of 150 tons (1.3 MN) was applied. During loading the die temperature dropped to 1500-1550F (816-843C). For this trial, time keeping started immediately upon full load achievement. After 10 minutes there was a 10-minute load interruption due to an electrical malfunction. After a dwell time of 15 minutes under load, ejection was attempted. At this time the die temperature was in excess of 1650F (900C). All attempts to eject the part and the top punch were futile.

The die set was disassembled, the bottom punch was removed and a hole was drilled through the forging to expose the top punch. The top punch was then pushed out of the die block. Several features of the stuck forging were apparent. The bottom bar stock section had lightly flashed around the bottom punch. The top of the preform had significantly flashed up around the top punch, as shown in Figure 4-13. The maximum flash height was aprpoximately 0.75 inches (0.02 m). Complete die fill around the top and bottom of the forging was observed. No gap at the shaft/P/M interface was seen, as the initially circular interface was deformed into a slightly elliptical cross section.

Removal of the forging from the die block remained impossible even after the top punch was removed. Therefore, the forging was leached out of the die block with nitric acid. The die block was heated to ∿180F (82C) and acid was fed into the die cavity. Interestingly, the bar stock shaft dissolved at a faster rate than the P/M section. The flash and surface in contact with the die block were very difficult to dissolve.

4.6.5 Conclusion from the Second Trial

Several conclusions or directions for future trials could be made after this unsuccessful trial.

First, the LF-22/boron nitride coating was not adequate. Indications of welding between the forging and die were present because of the difficulty in dissolving away the last traces of the forging from the die wall.

Second, the pressure, time, preheat and forging temperatures were sufficient to yield a quality forging. Die fill was complete and the shaft/P/M interface was well-bonded from all observations.

Third, areas of concern are the high preheat temperature of 1750F (954C), which could have reduced the effect of the coating, and the inability to rapidly heat the die above the final forging temperature to allow thermal expansion differences to relieve internal stresses. Also, the ejection cylinder did not supply adequate pressure for ejection.

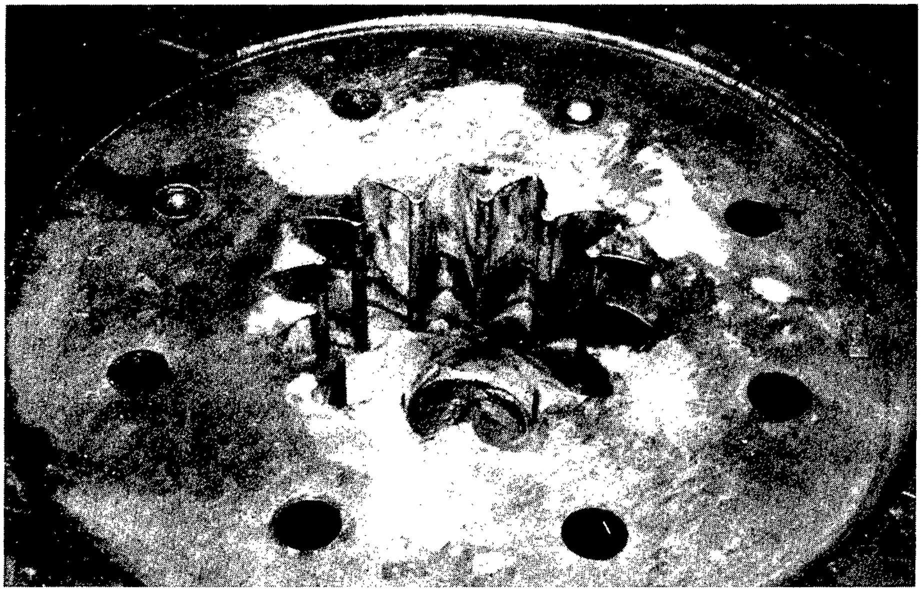


Figure 4-13. Flash Formed Between the Die Wall and Top Punch During Isoforging of the Pinion Gear. Shown is the Die Block Top, the Gear-Shaped Cavity, the Top of the Stuck Forging with a Hole Drilled in It and the Flash.

4.7 Spur Pinion Gear Forging - Third Iteration

Because of the major problem of ejection experienced on the second trial, it was decided that coupons of ∿0.5 inch (0.13 m) thickness should be forged by blanking off the gear cavity. These coupons would have the full gear cross sectional shape so that geometry and surface finish could be examined. Also, the limited ejection system was thought to be capable of ejecting these coupons. If the coupons were successful, one final full size trial would be made.

4.7.1 Coupon Preform Fabrication

Test coupons were made by slicing up full size sintered preforms. The coupon cross section was therefore identical to that of a full size preform. The height of the coupon was initially ∿0.75 inches (0.020 m). The test coupon preform included a bar stock center.

4.7.2 Preform Coating

A preform and two gear shaped punches were coated with a mixture of LF-22, CRT glass and boron nitride. The hot die cavity was sprayed with boric acid powder.

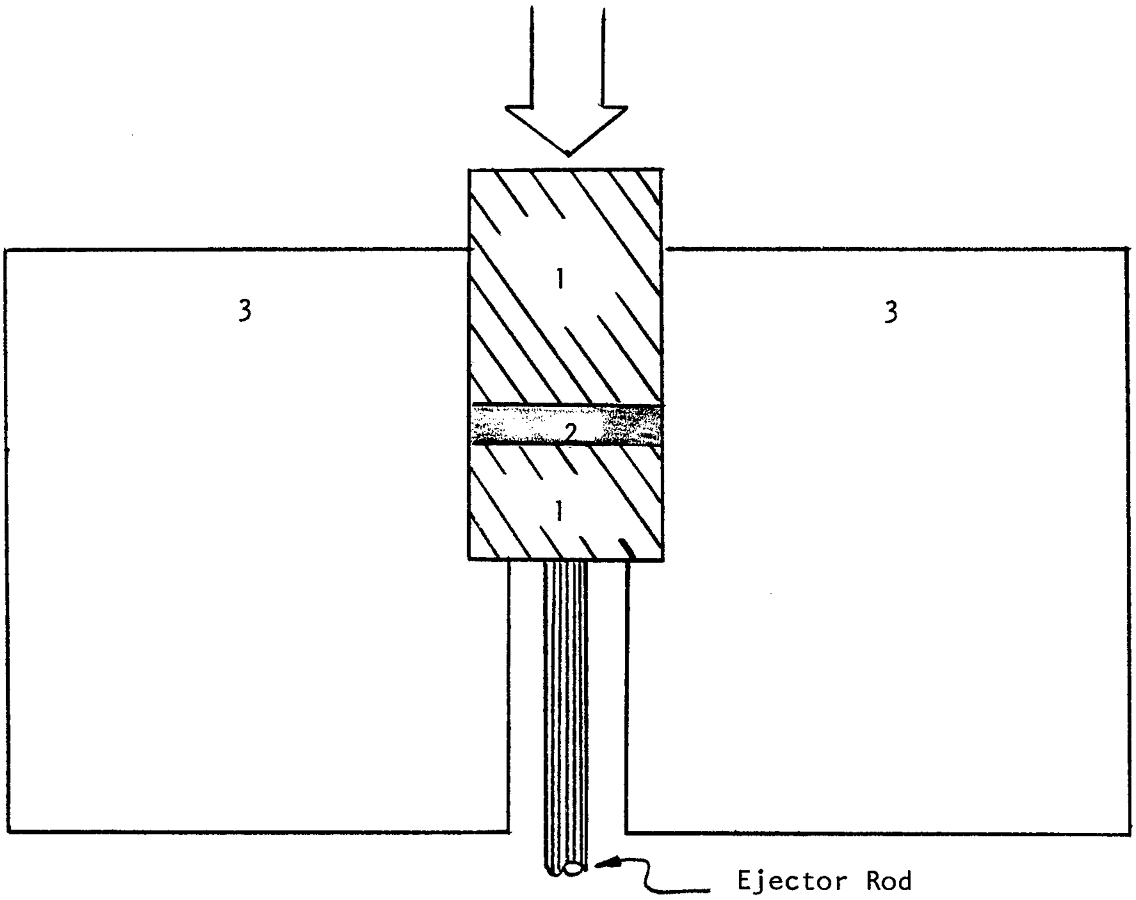
4.7.3 Preheat Practices

The coupon preform and the top punches were preheated to 1650F for 25 minutes in a reducing atmosphere of H_2 gas. The dies were preheated to 1550F (843C). The lower preheat temperatures were utilized to try to minimize coating burnoff of the preform and to allow thermal expansion capacity above the forging die temperature during ejection.

4.7.4 Gear Coupon Forging Trial

A schematic of the forging die with the blanked-off gear cavity is shown in Figure 4-14. The lower gear shaped punch was inserted into the die cavity and required light pressure to drop into the cavity. This was due to the heavy coating on the punch and the tight clearance gap between the punch and die. The hot preform was next inserted and then the top punch was positioned in the die cavity. During loading the die temperature dropped to 1450F (788C). A load of 105 tons (0.9 MN) was immediately applied and held for 15 to 17 minutes. In this time the die temperature had returned to 1550F (843C).

After the load was removed, the die top was exposed to cause cooling to the 1200-1250F (650-675C) temperature region. Then power was applied to attempt to rapidly heat the die to cause it to expand away from the coupon to aid ejection. Heating response was slow so that the piece heated as fast as the die. The result was the inability to conventionally eject the coupon. This was very disturbing in light of the low load, the glass-bearing coating and the reduced surface area of the coupon in comparison to the full size gear.



1. Gear Shaped Punch
2. P/M Preform
3. Die Block

Figure 4-14. Schematic of the Blanked-Off Forging Die Cavity for Forging Gear Segments.

The die set was taken apart and the coupon was pressed out using the ram of the press. It required 140 tons (1.2 MN) to break the coupon loose from the die. Once the coupon move, lower loads between 50 and 100 tons (0.4 to 0.9 MN) were used to keep it moving, but motion was not smooth. The top punch was easily removed after most of its length had cleared the die cavity. Once the coupon was free of the die, the lower gear shaped punch was tapped out by hand.

Several observations are worthy of mention. No major flash had formed around the top punch to lock the forging in the die. Die fill was incomplete, and surface finish was very poor. Lubricant was present on the top and botton surfaces of the forging but, by and large, was absent from the tooth faces. Coating still remained on the punches. Examination of the die cavity gave indications of coupon welding to the die wall. Also, the die cavity showed signs of pitting and slight scoring due to leaching and difficult ejections in previous trials.

4.7.5 Conclusions from the Third Trial

At this point, a halt was called to the laboratory program. A glass-bearing preform coating had proven to be totally unsatisfactory. Ejection of the coupon was unreasonably difficult and potentially injurious to the die.

5.0 ANALYSIS OF ISOTHERMAL FORGING OF STEEL POWDERS

5.1 Property Capabilities

The isothermal forging trials for the test coupons illustrated two features of isothermal forging of porous preforms:

1. The final properties are highly sensitive to processing variables. Residual porosity levels are related to the working temperature, pressure and time. For this study on 4620 steel powders, a pressure of at least 10 tsi (140 MPa) was needed for a dwell time of 15 minutes at a working temperature between 1600 and 1650F (870 to 900C). Given these conditions, tensile and impact properties similar to conventionally hot repressed powder forgings could be achieved.

2. A minimum deformation approach must be used for preform design. The low forging loads necessitate a major pore closure role to creep deformation. Because a high sintering temperature must be experienced prior to forging, the steel microstructure is not optimum for high creep rates. Thus, overall deformation modes involving gross lateral metal flow must be minimized. The major role of deformation is then limited to consolidation and not die fill.

   A second feature that limits isothermal forging to the minimum deformation approach is lubrication. Both side forging and upset forging resulted in incomplete die fill. Lubrication at the high die and workpiece temperature was ineffective in reducing friction.

The mechanical property levels that can be achieved by isothermal forging are equal to those that can be achieved by conventional P/M forging. Both ductility and toughness are improved by minimizing the oxygen content of the steel and by incorporating metal flow into the consolidation operation. Repressing represents the low end of the achievable properties and correlates with the property levels of isothermally forged pieces. These property levels are suitable for application as high integrity parts, provided proper design considerations are followed.

5.2 Process Limitations

The outcome of this program delineated some of the limitations of the isothermal forging process for steel powder preforms. First, lubrication is a major limiting factor, resulting in ejection problems for the gear forging. Second, the use of water atomized steel powder, which has a high initial oxygen content and requires high temperature sintering to reduce the oxygen level, means that minimum deformation preforms must be employed. Optimum microstructures for creep deformation can not be maintained during sintering. This limits the preform shape and puts a limit on mechanical properties. Third, since the plan area of the preform approximates the plan area of the forged part, the preform must be compacted

on a very large press or in a cold isostatic press since approximately 30 tsi (414 MPa) of pressure is needed. The alternative is to divide the preform into segments which are individually compacted, followed by sintering the setments together.

It is felt that this process is most applicable for forging pieces with large plan areas but low aspect ratios so that die wall contact is minimized. Thin ribs and webs have been forged previously, but draft should be employed in the die. The forging pressure should be maintained as at least 10 tsi and higher if possible so that dwell times may be shortened to less than 15 minutes at higher loads.

5.3 Economic Evaluation

The manufacturing cost for making a part is the summation of all the costs incurred during the process routing. For isothermal P/M forging amounts to:

$$TC = PC + SC + FC + MC + MH + M \tag{1}$$

where
- TC $\equiv$ total cost per part
- PC $\equiv$ preforming cost per part
- SC $\equiv$ sintering cost per part
- FC $\equiv$ forging cost per part
- MC $\equiv$ Machining and finishing costs per part
- MH $\equiv$ material handling cost per part
- M $\equiv$ raw materials cost per part.

The selling price of the part would be TC plus a profit factor. Each of the total cost factors has a set of cost concerns associated with it. The following paragraphs detail these cost breakdowns.

The preforming cost per part, PC, is dependent on the method of producing the preform, the dimensional accuracy needed, the number of preforms needed in a given manufacturing time period and the tooling cost. Mathematically this becomes:

$$PC = \left(\frac{DC}{DL} \cdot n\right) \Big/ n + \left(\frac{Pc}{n}\right) \Big/ \left(\frac{Ft}{n}\right) + L\ F_t + S \qquad (2)$$

where $DC \equiv$ the preform die cost

$DL \equiv$ the die life in terms of number of parts per die set

$n \equiv$ total number of preforms made

$Pc \equiv$ press charge per hour

$F_t \equiv$ total press time in hours

$L \equiv$ total labor charge per hour

$S \equiv$ setup charge.

Tool steel dies have a high initial cost in comparison to soft tooling for CIP, but they have a much greater life, C.F. 100,000 parts vs. 70 parts. The press charge per hour is usually in the \$50 to \$100 range and is roughly the same for mechanical, hydraulic and hydrostatic units. The speeds are widely different, with mechanical presses being capable of 100 to 120 parts per hour and hydraulic presses having rates of 20 to 30 parts per hour. CIP units for preform production are batch units and thus the production rate is dependent on part size and pessure vessel size as well as well as pump capacity. Powder loading and compact unloading is automated for hard die setups, but for CIP is a manual operation, albeit an unskilled operation. Setup costs for CIP are negligible but can be substantial for hard die setups.

The sintering cost per part, SC, is dependent on time at temperature, the cost of maintaining that temperature, the atmosphere cost and the furnace throughput. Thus:

$$SC = \left(\frac{SF_t}{n}\right) L + \left(SF_c \cdot n \cdot \frac{W}{S}\right) \Big/ n + Fx \qquad (3)$$

$SF_t \equiv$ total sintering time in furnace

$SF_c \equiv$ sintering furnace cost per hour

$S \equiv$ sintering speed - lbs./hr.

$W \equiv$ weight per part

$F_x \equiv$ fixturing costs per part.

The isothermal forging cost per part is comprised of the forging time per part (IF_t), the die cost (FDC) and die life (DC) and the preheating cost (furnace cost (PH_c) and time (PH_t).

$$FC = L \cdot IF_t + \left(\frac{FDC}{n}\right) \cdot \left(\frac{1}{\frac{DL}{n}}\right) + Ph_c \cdot PH_t + P_c \cdot IF_t + S \qquad (4)$$

The machining and finishing costs (MC) should be at a minimum since net or near-net shape is achieved. If possible milling should be avoided as it is a slow costly operation.

Material handling costs (MH) include storage of powder, compacts, sintered preforms and forgings. While the part exists as powder or is porous, humidity is harmful so special storage precautions should be taken. Blending and powder transfer are costs to be included in this handling charge.

The raw material costs include steel powder, graphite addition, lubricants and coatings.

5.3.1 Projected Economics of Pinion Gear Production by Isothermal Forging

The results of the forging program did not provide hard data that could be manipulated for economic forecasting. However, projections of costs can be made using standard time/cost schedules. Table 5-1 contains a cost/part breakdown for 1000 and 5000 piece lots. Assumptions are a labor plus overhead rate of $45/hour, 80% efficiency, and no G&A or fee is included. Inspection is also not included, but it would be identical for each group and to conventional practice. Major factors in this cost are the cost of isothermal forging and finishing costs. CIP also carries a high cost since it is a labor intensive area requiring manual bag fill, stripping and rack loading.

This cost breakdown does two things. One, it assumes that all of the current technical difficulty can be overcome. Two, it shows that for these low volume requirements P/M processing can be economical. In this case, even the high costs associated with isothermal processing are offset by reduced machining costs largely due to the elimination of hobbing to shape the gear teeth. For this reason the technical difficulties should be further investigated.

TABLE 5-1

Projected Cost/Part Breakdown for Isothermally Forged Gear

Step	Lot Size 1000 Pieces	Lot Size 5000 Pieces
1. Raw Materials:	$10.70	$10.70
(141.1 Lbs. Powder x $.415/Lb. + 22.1 Lbs Bar Stock x $.22/Lb.		
2. Preform Compaction (Including Tooling Cost):		
a) Hard Die Press-3 Sections	$ 2.65	$ 2.51
° (180 Compacts/Hr. x $\frac{1 \text{ Preform}}{3 \text{ Compacts}}$)		
° $10,000/Set with 50,000 Pieces Life		
° 4 Hr. Setup Time.		
b) CIP	$27.51	$26.66
° 3 Compacts Every 40 Minutes		
° 80 Pressings/Bag at $120/Bag		
° $700 Pattern Charge		
3. Sintering	$ 4.76	$ 4.76
° Continuous Throuthput Furnace 750 Lbs./Hr.		
° Optional Fixturing for Hard Die Pressed Preforms	($ 0.21)	($ 0.21)
4. Isothermal Forging	$47.94	$46.79
° Tooling Cost-$45,000 with Life of 5000 Pieces		
° 20-Min. Cycle Time		
° 32-Hour Setup		
5. Finishing (Machining and Heat Treating	$60.09	$60.09
° Preform Shaft Machining		
° SPT, Spline Cutting and Grinding		
° Normalize, Carburize		
6. Totals		
° Hard Die Route	$126.16	$125.06
° CIP Route	$151.00	$149.00

6.0 SUMMARY

To summarize, the results of this program show the isothermal forging of low alloy steel powders is not yet ready for commercialization. Lubrication during forging amounted to a major problem area as ejection from the die proved to be very difficult at best. However, the TiO-Form LF-22 coating did provide a good oxidation barrier for air-handling of heated preforms.

Isothermally forged test coupons of 4620 steel powder attained adequate tensile and toughness property levels if a pressure of 10 tsi (140 MPa) was applied for 15 minutes while the die and piece were at 1650F (900C). Shorter dwell times resulted in less than full density and low ductility and toughness values. Incorporation of metal flow into the forging step enhanced toughness and ductility, but because of the low forging load and poor lubrication die fill was incomplete. Therefore, minimum deformation appears to be a prerequisite for isothermal forging of steel powder preforms under these conditions.

Gear forging trials were not successful in producing a sound forging. Limited success was experienced on a low-load trial where die fill was incomplete. A full load was unsuccessful in that the forging could not be ejected from the die. Gear coupon forging revealed the true severity of the ejection problem as a 0.5 in. (.013 m) thick section required 140 tons to break it free of the die.

One side benefit of the program was the method used to make the punches and die cavity. Computer controlled wire EDM was used to cut the gear shaped punch and the electrodes used for die sinking. This insured a good fit between the punch and die cavity and represents a step forward in precision die making.

7.0 RECOMMENDATIONS

Because isothermal forging of steel powder preforms does project to be economical for specific cases, it is recommended that the lubrication/coating/die release problem be examined. Such a program would include several shapes where the aspect ratio and surface/volume ratios are varied to determine which shape categories are most viable for this processing.

Alternatives to isothermal forging in hydraulic presses would be isothermal forging in a hot isostatic press (HIP) or hot sand forging. Hot sand forging relies on pressure transfer via sand to the part being densified. For parts with loose dimensional tolerances and not requiring good surface finishes this may be viable on a select basis. On the other hand, HIP offers great potential for this area. Near-net shape capability is already a commercial reality for jet engine discs, although no surfaces are used as-HIP. For steel components, loose powder could be canned and HIP, or a preform could be pressed and then HIP. The latter route is economical if an easily applied can is used, e.g., glass, or the can is eliminated by achieving high density in the sintered preform. This processing offers the possibility of producing engineered parts where alloys are selectively applied where needed to optimize properties and minimize cost. The planetary ring gear of the XM-1 tank is suitable for this type of processing by HIP.

8.0 REFERENCES

1. F. T. Lally, I. J. Toth and J. DiBenedetto, "Forged Metal Powder Products", Technical Report on Contract DAAF01-70-C-0656, November 1971.

2. F. T. Lally and I. J. Toth, "Forged Metal Powder Gears", Technical Report on Contract DAAE07-72-C-0277, September 1974.

3. F. T. Lally and I. J. Toth, "Isothermal Forging of Precision Metal Powder Components", TRW Report ER-7569-5, July 1973.

4. A. Crowson and F. E. Anderson, "The Effects of Sintering Parameters and Particle Size Distributions on P/M Steel Forgings", Research Directorate, General T. J. Rodman Laboratory, Rock Island Arsenal, Rock Island Illinois.

5. 1971 Materials Engineering Materials Selector, P. 58.

6. B. L. Ferguson, "Toughness and Fatigue of Iron-Base P/M Forgings", Ph.D. Thesis, Drexel University, 1976.

7. "The Engineering Properties of Tungsten and Tungsten Alloys", DMIC Report No. 191, Battelle Memorial Institute, September 27, 1963.

APPENDIX I

HOOP STRESSES IN RINGS

Since a wire wound reinforcing ring was used on the forging die block, it is necessary to calculate the hoop stresses that can be generated in the wire and in the die block. The basic stress equations for thick walled pressure vessels are:

$$\sigma_r = -\frac{P_i\ r_i^2}{(r_o^2 - r_i^2)}\left[\frac{r_o^2}{r^2} - 1\right] - \frac{P_o\ r_o^2}{(r_o^2 - r_i^2)}\left[1 - \frac{r_i^2}{r^2}\right] \qquad \text{eq. (A-1)}$$

$$\sigma_\theta = \frac{P_i\ r_i^2}{(r_o^2 - r_i^2)}\left[\frac{r_o^2}{r^2} + 1\right] - \frac{P_o\ r_o^2}{(r_o^2 - r_i^2)}\left[1 + \frac{r_i^2}{r^2}\right] \qquad \text{eq. (A-2)}$$

where P_i and P_o are internal and external pressures, r_i and r_o are internal and overall radii and σ_r and σ_θ are the radial and hoop stresses respectively. For the case of a wire wrapped die, the problem becomes more complex because an intermediate pressure builds up between the die block and windings, and thermal expansions of the materials become important since the die operates at elevated temperatures.

In this case, the thermal expansion factor of the tungsten wire is approximately one-third that of the IN-100, so that the greater expansion drive of the die will affect an interference fit betweeen the die block and windings to generate a supportive circumferential load on the die block. The pressure generated on the die block by the interference fit is:

$$P_s = \delta/r_2/\left\{[(r_2^2 + r_1^2)/(r_2^2 - r_1^2) - \nu_1]/E_1 + [(r_3^2 + r_2^2)/(r_3^2 - r_2^2) + \nu_2]/E_2\right\} \qquad \text{eq. (A-3)}$$

where δ is the magnitude of the interference; r_1, r_2 and r_3 are the inner, interface and outer radii; ν_1, ν_2, E_1 and E_2 are the Poisson ratios and Young's Moduli of the two materials and P_s is a pressure. The stresses due to the pressure (P_s) caused by the interference then reduce to those given in Equations (A-1) and (A-2). A table showing the pressure (P_s) and the die and wire stresses σ_θ and σ_r as they vary with interference (δ) is found in Table A-1.

An appropriate interference seems to be 0.03 to 0.04 inches (7.6×10^{-4} to 1.0×10^{-3}m). It is felt that loose winding, wire cross-overs, twist and kinks will result in greater expansion of the windings than expected so that a smaller than anticipated interference will result. Therefore, greater interferences than mentioned above could be tolerated.

TABLE A-1

Interference - Pressure - Stress Relationships

		Die Block				Wire Winding			
		δ_r (ksi)		σ_θ (ksi)		σ_r (ksi)		σ_θ (ksi)	
δ	P_s (ksi)	I.D.	Interface	I.D.	Interface	Interface	O.D.	Interface	O.D.
0.01	5.6	0	-5.6	-12.9	-7.3	5.6	0	72.9	67.3
0.02	11.2	0	-11.2	-25.7	-14.5	11.2	0	145.8	134.6
0.03	16.8	0	-16.8	-38.6	-21.8	16.8	0	218.7	20.19
0.04	22.4	0	-22.4	-51.5	-29.1	22.4	0	291.6	269.2
0.05	28.0	0	-28.0	-64.3	-36.3	28.0	0	364.5	336.5
0.06	33.6	0	-33.6	-77.2	-43.6	33.6	0	437.4	403.8

Note: 1) 1 ksi = 6.89 MPa

2) 1 inch = 0.0254 M

3) I.D. = 4.5 in.

Interface Dia. = 12.5 in.

O.D. = 13.5 in.

4) Calculated at no forging load.

DISTRIBUTION LIST

	Copies
DEFENSE DOCUMENTATION CENTER ATTN: TIPDR Cameron Station Alexandria, VA 22314	12
Commander US ARMY MATERIEL DEVELOPMENT AND READINESS COMMAND ATTN: DRCMT 5001 Eisenhower Avenue Alexandria, VA 22333	1
Director US ARMY MATERIALS AND MECHANICS RESEARCH CENTER ATTN: DRXMR-M Watertown, MA 02172	2
Director US ARMY INDUSTRIAL BASE ENGINEERING ACTIVITY ATTN: DRXIB-MT Rock Island Arsenal Rock Island, IL 61299	3
Commander US NAVY MATERIEL INDUSTRIAL RESOURCES OFFICE ATTN: Code 044 Philadelphia, PA 19112	1
Commander AIR FORCE MATERIALS LABORATORY ATTN: LTM Wright-Patterson AFB, OH 45433	1
Commander US ARMY TACOM ATTN: DRSTA-UL (Technical Library) Warren, MI 48090	2